Noise Level in Indoor Sports Facilities and Factors Affecting the Acoustic Environment

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Abstract

Poor acoustic environments coupled with excessive noise levels in indoor sports facilities can lead to annoyance and miscommunication between occupants, or can potentially cause negative long-term effects on auditory health.

In this thesis, 18 sports halls across 14 different facilities in the Helsinki metro area were measured with respect to three acoustic parameters (reverberation time, Speech Transmission Index (STI), and weighted noise level) in order to determine the quality of their respective acoustic environments, and whether adherence to current regulation was maintained.

The work is part of the broader LIIKU project, which investigates the indoor air environment in the selected facilities. Regulations currently use reverberation time almost exclusively as the parameter determining the quality of an acoustic environment.

Measurements were split into empty room impulse response measurements and occupied room noise level measurements. Procedures were kept as similar as possible to minimize the amount of variables affecting results.

The results showed that less than half of the halls meet current regulation limit values. However, certain halls that do not meet limits exhibit better STI results that some halls that do, indicating potentially acceptable acoustic environments. Noise level measurements were heavily affected by the Covid-19 pandemic due to restrictions on the capacity of indoor facilities. These results are therefore not representative of an everyday situation.

Current Finnish regulations have been shown to not be adequate in determining a good acoustic environment, as reverberation time is not the sole factor. STI should be also included in new regulations, multiple sets of limit values should be established to account for the wide variety of sports hall types, and steps should be taken to improve the acoustic qualities of the halls that vastly exceed the limit values.

Keywords acoustics, acoustic quality, indoor environment quality, noise, reverberation, sports hall, STI

Preface

I would like to thank my supervisor, Prof. Heidi Salonen, for her guidance and support as head of the LIIKU project, as well as for giving me the opportunity to join the team in the first place.

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On the logistical side of things, I'm grateful to Camilla, the LIIKU project manager, for organizing the measurement schedule and making sure that the visits ran as smoothly as possible, especially considering the tricky circumstances. On measurement visits, I also had the pleasure of working alongside Tuomas, who was also carrying out his Master's thesis with the LIIKU project (investigating indoor air contaminants).

Finally, special thanks to Mom, Dad, and the rest of the family who read through and reviewed this document, providing useful insight and suggestions. They are my biggest critics and their help has been invaluable in making this thesis as good as possible.

Otaniemi, 30.7.2021

Gabriele Del Brenna

Contents

Symbols and abbreviations

Symbols

a	total room sound absorption
c	propagation velocity [m s^{-1}]
f	frequency [Hz]
$f(t)$	inverse filter of the input in time domain
$h(t)$	system transfer function in time domain
$H(f)$	system transfer function in frequency domain
I	sound intensity [W m^{-2}]
k	wave number [m^{-1}]
K	bulk modulus [Pa]
L_p	sound pressure level [dB]
L_{eq}	equivalent noise level [dB]
L_{Aeq}	A-weighted equivalent noise level [dBA]
L_{Zeq}	Z-weighted equivalent noise level [dBZ]
m	m-value
$n(t)$	system noise in time domain
p	pressure [Pa]
p_0	maximum pressure [Pa]
p_{ref}	reference pressure = 20 μ Pa
R	sound reflection coefficient
t	time [s]
T_{60}	reverberation time [s]
V	volume [m^3]
x	displacement [m]
$x(t)$	system input in time domain
$X(f)$	system input in frequency domain
$y(t)$	system output in time domain
$Y(f)$	system output in frequency domain
Z	acoustic impedance [Pa s m^{-3}]
Z_c	specific acoustic impedance [Pa s m^{-1}]
α	sound absorption coefficient
ρ	material density [kg m^{-3}]
ω	angular frequency [rad s^{-1}]

Operators

$*$	linear convolution
$\circledast$	circular convolution

Abbreviations

ANC	Acoustics & Noise Consultants
AQ	Acoustic Quality
EDT	Early Decay Time [s]
IAQ	Indoor Air Quality
IEQ	Indoor Environment Quality
LQ	Light Quality
MTF	Modulation Transfer Function
RIL	Suomen Rakennusinsinöörien Liitto (Finnish Association of Civil Engineers)
SNR	Signal-to-Noise Ratio [dB]
SNR_{app}	Spparent Signal-to-Noise Ratio [dB]
SPL	Sound Pressure Level [dB]
STI	Speech Transmission Index
TC	Thermal Condition
THL	Terveyden ja Hyvinvoinnin Laitos (National Institute for Health and Welfare)
TTL	Työterveyslaitos (Finnish Institute of Occupational Health)

1 Introduction

Indoor Environment Quality (IEQ) is an assessment of factors affecting the perception and experience of people within the indoor environment. Typically, IEQ has been associated with the Indoor Air Quality (IAQ), which measures the presence of pollutants and other potentially harmful substances in a space, as well as ventilation performance. Over time, the concept of IEQ has been expanded to include Thermal Condition (TC), Light Quality (LQ), and Acoustic Quality (AQ) [1, 2].

These four parameters have been shown to adversely affect productivity and occupant comfort in open plan offices [2, 3, 4, 5]. Moreover, AQ was found to be the second leading cause for dissatisfaction in the workplace [2]. While standards for the measurement of acoustic parameters [6, 7] have been developed for common spaces, such as open plan offices and performance spaces, sports facilities lack standardized measurement procedures for evaluating their acoustic environment. Legal regulations and parameter limit values exist mainly for office spaces and housing, but implementing them to cover the wide variety of sports hall types is complicated due to factors including hall size and geometry, intended hall purpose, as well as sports equipment, which can all have significant effects on the values of measured acoustic parameters. There is currently no comprehensive set of acoustic parameter limits for sports halls in Finland. The RIL-243-2-2007 regulation gives limits for one parameter (reverberation time), based only on the ceiling height of a hall [8].

Indoor sports facilities are usually built to be multipurpose (i.e., the same space can be used for a variety of sports and activities). Particularly in school gymnasiums, different activities can be simultaneously carried out in the same space. The presence of sound sources, such as speech, sports noise (balls bouncing, footsteps, and other impacts), and occasionally music, combined with a poor acoustic environment can cause annoyance for occupants, miscommunication between instructors and participants, as well as potentially hazardous working conditions [9].

The LIIKU project, carried out by the Aalto Department of Civil Engineering in collaboration with the Finnish Institute of Occupational Health (TTL) and the National Institute for Health and Welfare (THL), aims to provide new information on the IEQ of various sports facilities in the Helsinki metro area as well as the impact of the IEQ on the well-being of occupants. This thesis focuses on the acoustics-related research of the LIIKU project.

The goal of this work is to determine the acoustic environment in 14 sports facilities in terms of three acoustic parameters: reverberation time, Speech Transmission Index (STI), and weighted noise level. The thesis aims to contribute to the development of comprehensive acoustic regulation for sports halls in Finland. To achieve this goal, the thesis will compare the three room acoustic parameters against current Finnish building regulations [8] in order to evaluate the suitability of these environments for their intended purpose. As individual perceptions may not always correspond to objective data, a subjective study administered by the LIIKU Project will be used to verify the extent to which user experience agrees with measured data. For the subjective study, a questionnaire will be sent to staff and customers of sports facilities about the respondents' perception of the acoustic environment. The scope of this thesis will be limited to one or two halls per facility, similar in nature, in order to create a common basis for comparing of results across different facilities.

The thesis is structured as follows. Chapter 2 reviews the principles and theory on sound and acoustics, with a focus on the concepts relevant to the measurements. Chapter 3 describes the methods, procedures and equipment used to measure the acoustic parameters. Chapter 4 presents the results and compares the data from the different sports facilities, as well as evaluating it against the Finnish building regulations. Chapter 5 discusses the results in more detail, as well as suggesting improvements for the facilities where applicable. Chapter 6 concludes the thesis by evaluating the contribution of this thesis and suggesting directions for future work.

1.1 Limitations

This thesis was carried out as the Covid-19 pandemic was ongoing, and restrictions were imposed in Finland. For most of the period of work, sports facilities were highly limited in terms of capacity, as well as who could access them. It is for this reason that the noise level measurements were significantly impacted, both in terms of quantity and quality, as not all halls could be visited, and the data collected does not represent a realistic ordinary situation.

The LIIKU questionnaire was also delayed, and is expected to be carried out in the autumn. The subjective data is therefore unavailable, and consequently this aspect of the results has been removed from the scope of the thesis.

2 Theory

This chapter serves as a guide to contextualize the purpose of the thesis, by laying out the theoretical concepts essential to understanding both the measurement process and the results obtained from it. Indoor sports facilities are presented first, with a focus on the types relevant to the measurements, as well as what the acoustic environment is typically expected to be like. The concept of sound is explored in the following section, and the three acoustic parameters measured are explained at the end.

2.1 Indoor Sports Facilities

Indoor sports facilities are areas designated for the purpose of sports and other physical activities. They include a broad range of types, spanning from gymnasiums to bowling alleys, and can be either individual or multipurpose. Facilities are typically large complexes that house many halls designated for different activities (e.g., weightlifting gyms, basketball courts, gymnastics halls, etc.). Some halls include bleachers for viewing purposes as well. In this thesis, 14 facilities were visited, and a total of 18 halls were measured. The majority of halls measured were of the gymnasium type, with one large court used for a variety of sports, such as basketball, volleyball, or futsal. Examples are shown in Figure 1.

Figure 1: Three examples of the sports halls measured. From top left, clockwise: Myyrmäki, Liikuntamylly, and Leppävaara

Being involved in sports and physical activity on a regular basis contributes to overall improved health [10]. Indoor sports facilities allow for improved comfort and safety as the environment can be controlled and shielded from the elements. In areas such as Northern Europe, the importance of indoor sports facilities is amplified by the colder climate. This causes outdoor sports to experience a shorter accessibility season compared to indoor sports. Access to well-functioning indoor facilities is therefore crucial to ensure a high level of participation in sports and physical activity by the population [11].

Sports and physical activity require movement as well as equipment in most cases, and this introduces different sound sources into the environment. Outdoor sports environments do not suffer from poor acoustic environments as they are essentially devoid of sound reflection, with the exception of locations such as stadiums. Indoor sports facilities must ensure a suitable acoustic environment that avoids excessive reverberation, which can lead to annoying or harmful conditions, and allows for an appropriate level of speech transmission, so that communication between coaches and players, for example, is understandable.

2.1.1 Acoustic Environment in Sports Halls

The acoustic environment in sports halls is characterized by a large variety of sound sources; the most common being speech, music, and impact sounds. The acoustic environment is affected by many factors, including the volume of the space, surface materials, objects present in the space, as well as the geometry of the space itself. Gymnasiums are typically large, mostly empty, cuboid-shaped halls with hard surfaces. The latter aspect leads to high amounts of sound reflection throughout the space. Gymnastics halls are also typically large, but the mostly soft equipment used for the sport (e.g., foam pits and mats) reduces sound reflection.

Finland has invested in the construction of underground shelters since the post-war period, and the Finnish Civil Defense Act states that the shelters must also accommodate peacetime purposes [12]. Many shelters around the Helsinki area house sports facilities. These spaces are mainly characterized by concave hard rock walls, which are strong reflective surfaces.

Acoustics with a focus on buildings is a relatively new field of research, although there is evidence that Italian architects and scientists were aware of certain acoustic features, such as sound diffusion and the acoustic properties of certain materials, when designing music halls and theaters between the 16^{th} and 19^{th} Centuries [13]. However, while there are currently acoustic regulations for different types of buildings throughout Europe, they are quite recent, and do not retroactively apply to buildings already existing before regulations went into effect. Subsequently, old buildings exhibiting poor acoustic environments are usually not required to make improvements, even when the spaces are renovated [14].

Sports halls encapsulate a wide range of space types, purposes, shapes, and sizes. It is for this reason that one comprehensive regulation for all halls is complicated to produce. Guidelines for reverberation time in school buildings have been established in Japan [15] and the United Kingdom [16], including school gymnasiums. However, the Japanese guidelines only address gymnasiums with a volume of around 5000 m^3, whereas the British guidelines express their limits in terms of floor area, and the Finnish regulation assigns sports hall acoustic categories based on ceiling height.

In 2017, the Finnish Ministry of the Environment published new regulations for the acoustic environment of buildings, using both reverberation time and Speech Transmission Index (STI) as parameters [17]. However, the only mention of sports halls in this regulation is for halls up to 1500 m^3 in volume, which does not apply to the majority of the spaces measured in this thesis.

In their paper, Nijs and Schuur [18] suggest that reverberation time, which is commonly used in acoustic regulations as a measure of good/bad acoustic environments, is not a suitable parameter for this purpose due to its reliance on the volume of the space. They suggest that STI would be a better alternative to evaluate the acoustical environment within a sports hall. A practical example given in the paper was a newly constructed athletics hall, with a measured reverberation time of 2.3 s, which was above the Dutch government's limit of 1.8 s. Despite this, the occupants did not have issues with the acoustic environment, even expressing that they liked it.

2.2 Physical Concept of Sound

Sound is defined as the propagation of a pressure wave through a medium. A pressure wave is a longitudinal wave produced by the pressure variation caused by the vibration of particles or objects within the medium [19]. The wave can be propagated between different media, as long as they are sound-transmitting (e.g., sounds cannot be heard in space due to the absence of matter in a vacuum). In the time domain, a sound wave is described by the following function.

$$p(t) = p_0 \sin(\omega t \pm kx) \tag{1}$$

where $p(t)$ is pressure as a function of time, p_0 is amplitude (i.e., maximum pressure), ω is the angular frequency, and k is the wave number. ω is expressed in radians per second, and can be converted to Hertz through $f = \frac{\omega}{2\pi}$.

Sounds can be approximated as summations of sinusoids, each with their own frequency. Each time domain sound has its own frequency domain form, which is an equivalent way of representing the signal, but showing its frequency components and their relative prevalence within the sound. The two representations of the same sound are shown in Figure 2.

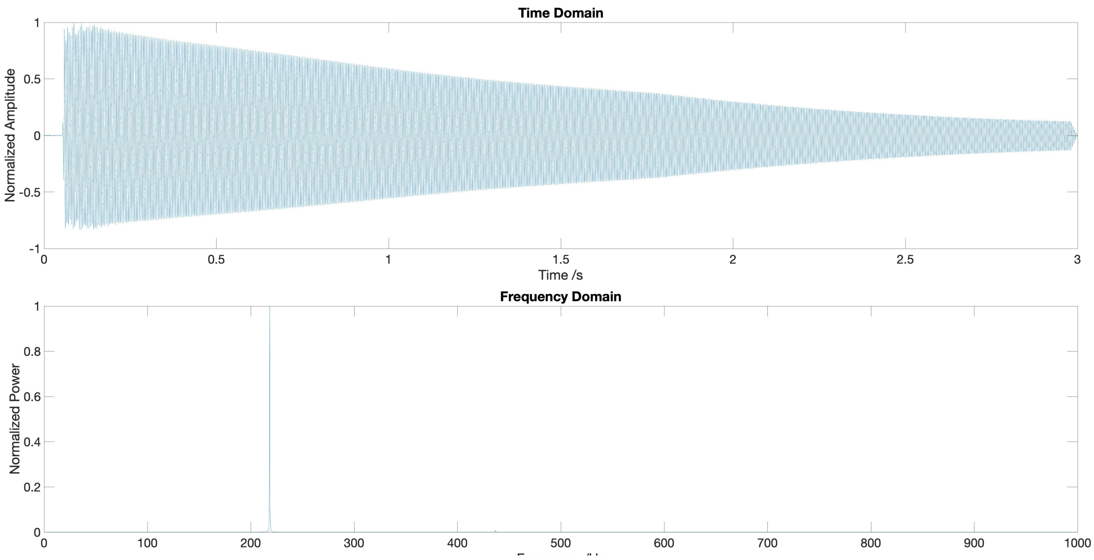

Figure 2: Time and frequency domain representations of sound

The graphs show a short segment of an A note being played on an electric bass, on the 14^{th} fret of the G string. This corresponds to $A_3 = 220$ Hz. In reality, the note was found to be 218 Hz. As this sound is almost a pure tone, it is very close in shape to a single sinusoid at the base frequency. Due to harmonics, the vibrating string will also produce sounds at integer multiples of the base frequency, but with much lower power relative to it. In the frequency domain, this is shown by a large peak at the base frequency, and a very small second peak at 436 Hz. There are a large number of harmonics excited by the original signal, but they are so relatively small that they are imperceptible, as well as invisible on the y-axis scale. It is for this reason that the frequency axis has been limited to 1 kHz. Converting the y-axis unit into a more easily comprehensible metric, the Decibel, can show the higher harmonics, as displayed in Figure 3. This is explained in the next section.

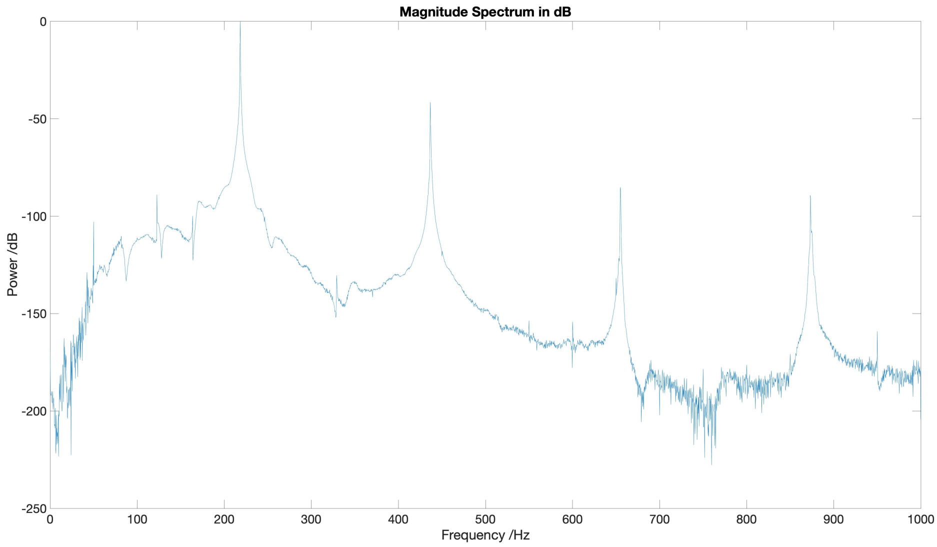

Figure 3: Frequency domain representation in Decibels

Similarly to light waves, sound waves can experience reflection, refraction, and absorption.

Reflection and absorption are opposite concepts. Like light, the angle of incidence is equal to the angle of reflection at the boundary. Building materials are often defined by their absorption coefficient, calculated as the ratio between incident sound intensity and sound intensity absorbed.

$$\alpha = \frac{I_a}{I_i} \tag{2}$$

The reflection coefficient, R can be determined by

$$R = \sqrt{1 - \alpha} \tag{3}$$

The two main factors determining the reflection/absorption of materials are how hard and how dense the material is. This can alternatively be expressed by the propagation velocity of a longitudinal wave in a medium, c (m s^{-1}).

$$c = \sqrt{\frac{K}{\rho}} \tag{4}$$

A lower velocity corresponds to a lower acoustic impedance. Acoustic impedance is a measure of the extent to which a material resists acoustic flow through it as a result of acoustic pressure being exerted onto it. While acoustic impedance, Z (Pa s m^{-3}), takes into account both the medium and its geometry, specific acoustic impedance, Z_c (Pa s m^{-1}), only concerns the medium itself. Where K is the bulk modulus (Pa): a measure of how hard a material is. ρ is its density (kg m^{-3}). Specific acoustic impedance of porous materials is also expressed in terms of K and ρ [20].

$$Z_c = \sqrt{K\rho} \tag{5}$$

For example, a coarse concrete block has an absorption coefficient value of between 0.3 and 0.4. When the block is painted over, as is common in buildings, the value drops to between 0.05 and 0.07 [21]. A coarse block of concrete has some porosity to it, and a coat of paint drastically reduces it. While the material remains essentially as hard as before, the paint has covered holes, resulting in a denser surface and therefore a higher acoustic impedance, leading to a much lower absorption coefficient.

Absorption coefficient values are dependent on frequency. In general, materials will exhibit higher absorption coefficient values as frequency increases. Higher frequency waves have higher energy compared to low frequency waves, and therefore also lose more energy as they propagate.

There are exceptions to this generalization, as resonances and antiresonances in materials can cause drops or spikes in absorption coefficient values at certain frequencies. In the specific case of buildings, walls are typically large structures and therefore exhibit resonances are low frequencies. This makes it easier for resonance frequencies to pass through. Higher absorption can be achieved by applying more absorptive materials to wall surfaces, or constructing walls consisting of multiple different materials that have different resonance frequencies.

2.2.1 Characterization of Sound

The y-axes in Figure 1 show normalized amplitude/power. However, the Pascal as a unit for sound pressure is not easily relatable in an everyday context. For this reason, the Decibel (dB) is mainly used when talking about the magnitude of a sound. Decibels are a logarithmic comparison of two quantities, calculated by the following equation.

$$dB = 10\log_{10}(\frac{q_1}{q_2}) \leftrightarrow \frac{q_1}{q_2} = 10^{\frac{dB}{10}} \tag{6}$$

Logarithms allow for very large numbers to be more easily comprehended (e.g. a factor of one million between two quantities is equivalent to a difference of 120 dB). In Figure 2, the dB difference between the base frequency and the closest harmonic is around 42 dB, indicating that the 436 Hz component of the sound is approximately 125 times less powerful than the base frequency of 218 Hz. The next harmonics are between 85 and 90 dB below the base frequency, rendering them impossible for the ear to isolate from the main components of the sound.

In acoustics, Sound Pressure Level (SPL) is the most common dB quantity used to describe how loud a sound is. Sound pressure is defined as "the deviation of pressure from the static pressure in a medium, most often air, due to a sound wave at a specific point in space," [22]. SPL (dB), L_p, is defined as follows.

$$L_p = 10 \log_{10}(\frac{p_1}{p_{ref}})^2 = 20 \log_{10} \frac{p_1}{p_{ref}} \tag{7}$$

where p_1 is the pressure of the sound being studied and p_{ref} is the reference pressure, corresponding to 20 μPa: the threshold of human hearing. It follows that 0 dB is essentially absolute silence to our ears, and an increase of 3 dB corresponds to a doubling in sound pressure. Negative values are also possible, but are imperceptible to humans. Figure 4 shows common sound sources and their respective levels in dB.

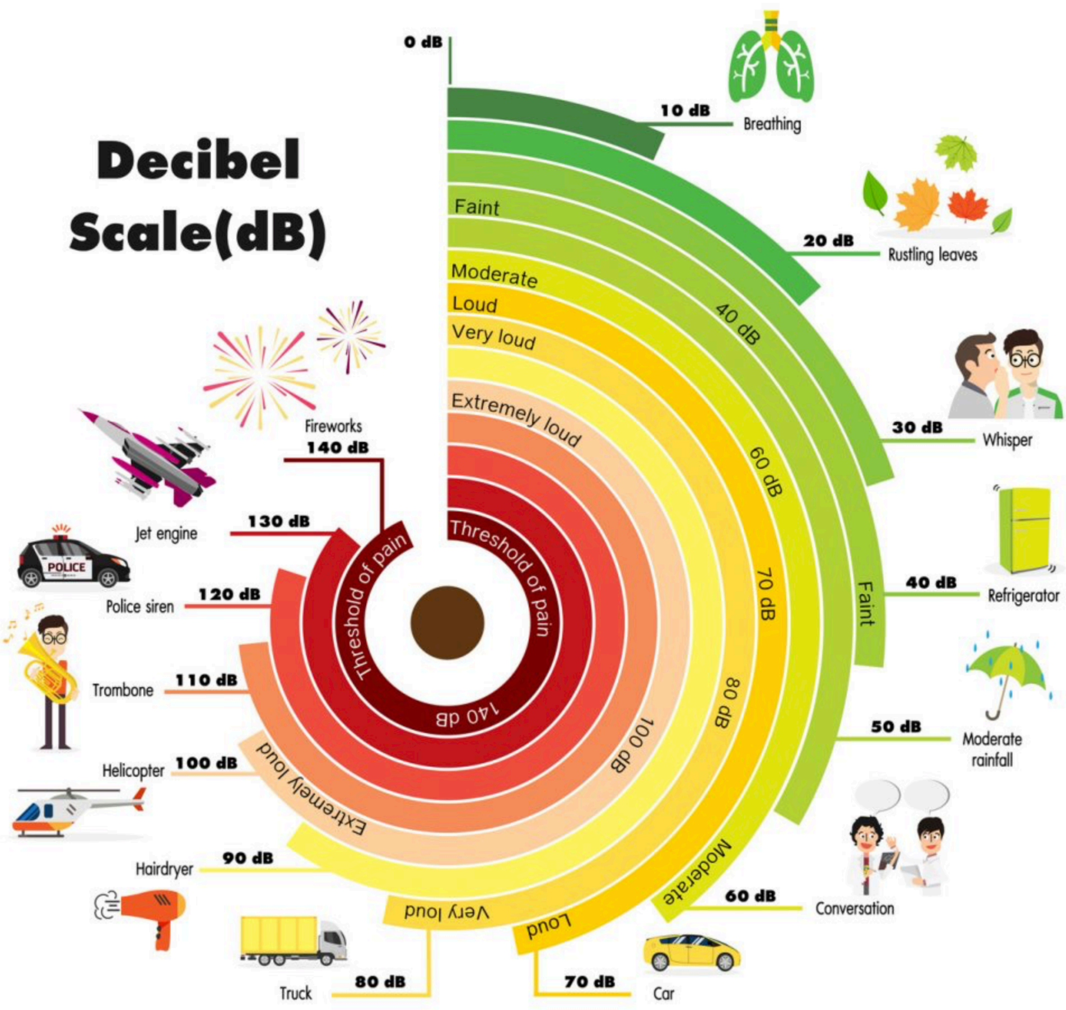

Figure 4: Common sound source levels. Reprinted from [28]

Human hearing is logarithmic in nature, and therefore we represent acoustic data in the same way. The range of hearing is between 20 Hz and 20 kHz, and is often broken down into octave or one third octave bands in order to have a clearer picture of the frequency content for a given measurement. There are 11 octave bands and 33 one third octave bands, the latter closely represent the ability of our auditory system in distinguishing between different frequencies [23]. Figure 5 shows the same bass sound from previous figures represented in octave and one third octave bands between 20 Hz and 20 kHz.

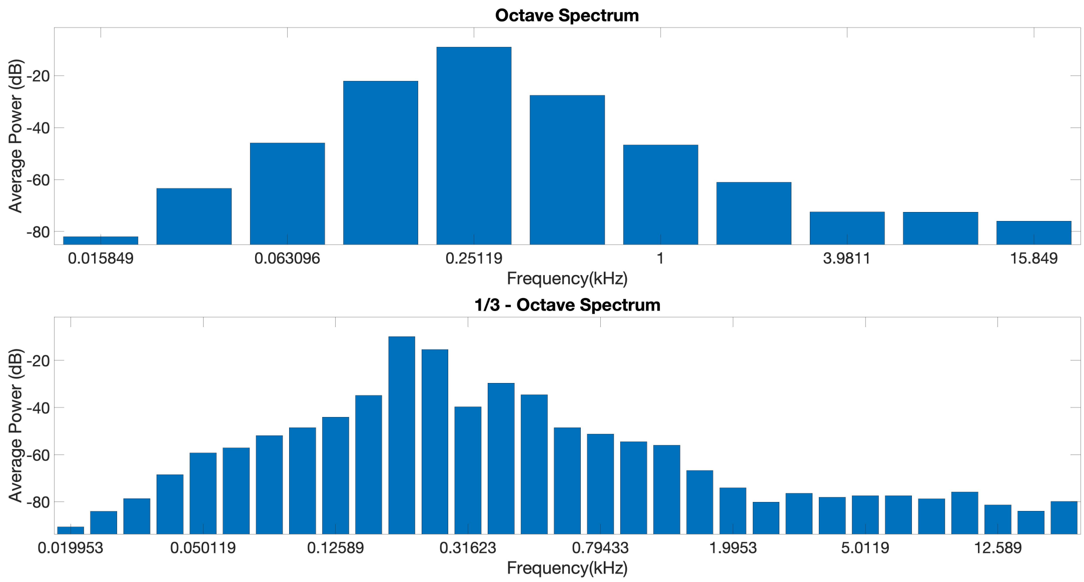

Figure 5: Octave and one third octave band representations of sound

Not all sounds are perceived equally by the human auditory system. It has been suggested that the evolution of the cochlea in parallel with the development of speech in human civilization may have contributed to our particular frequency tuning [24]. Different frequencies of different SPL values can sound equally as loud to a person. This was determined experimentally by Fletcher and Munson in 1933, who published the first equal loudness contours [25]. The current standard, ISO-226, was based on Robinson and Dadson's research [26], and subsequently revised most recently in 2003. This is shown in Figure 6.

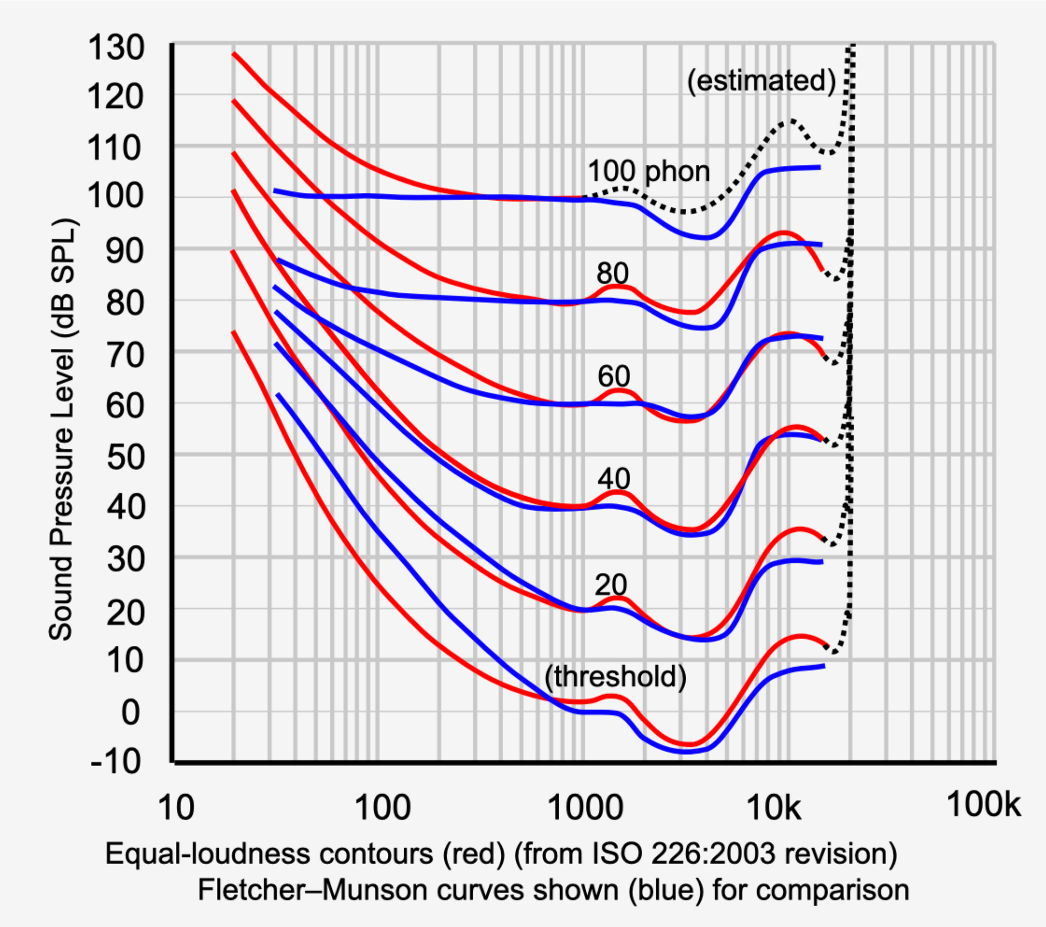

Figure 6: ISO 226:2003 equal loudness contours. Reprinted from [27]

2.3 Acoustical Parameters

There are many parameters and measurements that we use in order to describe the acoustic environment around us. This thesis is limited to the three parameters (reverberation time, STI, and weighted noise level) that are most relevant to it, and will be used in the measurements.

2.3.1 Frequency Weightings

Sound pressure and SPL are the most important measures of sound, as they directly relate to what we perceive (i.e., the intensity of a sound). However, as mentioned previously, the human auditory system has evolved to prioritize the perception of certain frequencies over others, focusing on the sounds that are most important in daily life, such as speech. On the other hand, measurement microphones and sound level meters are engineered to have as flat a frequency as possible over the audible range in order to provide the most objective data possible.

In order to reconcile the two, frequency weightings are applied to sound level measurements in order to present them into a relatable context. There are three weightings, namely Z, A, and C-weightings.

Z-weighting applies no filter to the recorded sound, and therefore aims to record the source in its absolute state. This is used when the focus of the measurement is to analyze the source, rather than looking at how people may perceive the sound from that source.

The A-weighting filter drastically reduces the level of the very low and very high frequencies, while very slightly amplifying the range between 1 and 4 kHz. This represents the normal state of human hearing, and is the most commonly used weighting for a majority of situations.

The C-weighting filter also is shaped to mimic human hearing, but at high pressure levels (typically over 100 dB). At these levels, the ear's response is flat across most of the spectrum, except in the very low and very high frequency regions. C-weighting is mainly used for sustained high noise environments (e.g., machine noise in factories), or peak noise measurements.

Figure 7 shows the relative differences between the three weighting curves [29].

2.3.2 Impulse Response

Sound is always affected by the environment in which it is propagated. Acoustic waves exhibit similar behavior to electromagnetic waves. They can reflect off surfaces, refract around objects, and attenuate either over time or by absorption. The geometry, arrangement, and surface materials of a room can all change the characteristics of a sound played within it.

An impulse response is a quick way of capturing the effect that a certain room has on a very loud and short excitation signal. This can take many forms such as a click, a noise burst, or a sine sweep over the audible frequency range. Recording the signal played within the room of interest will result in the combination of the

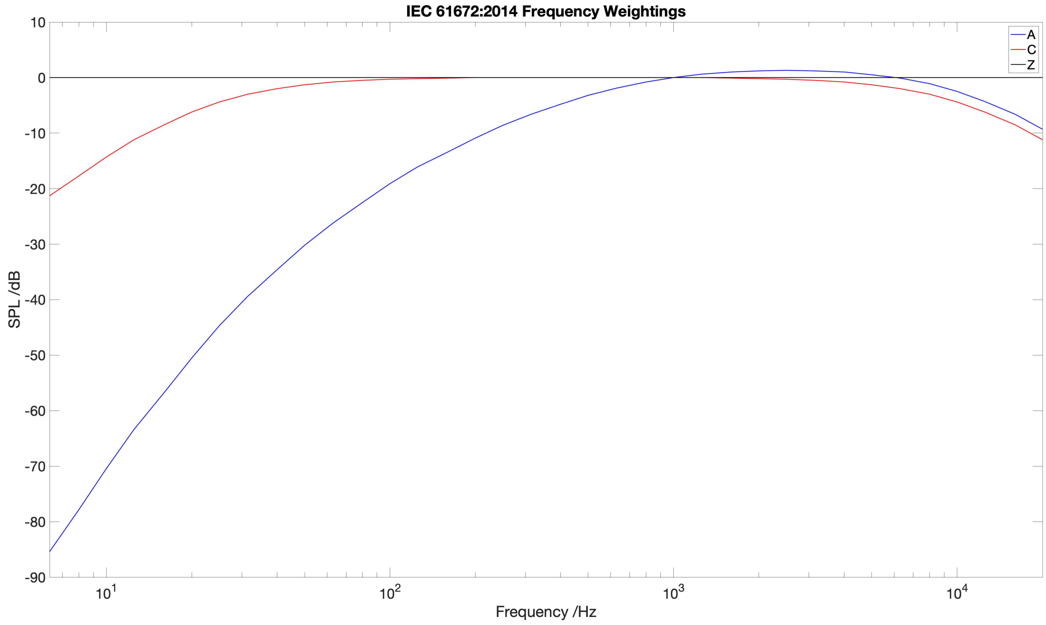

Figure 7: Frequency weighting curves

signal and the effect of the room. Figure 8 shows an example of a recorded impulse response.

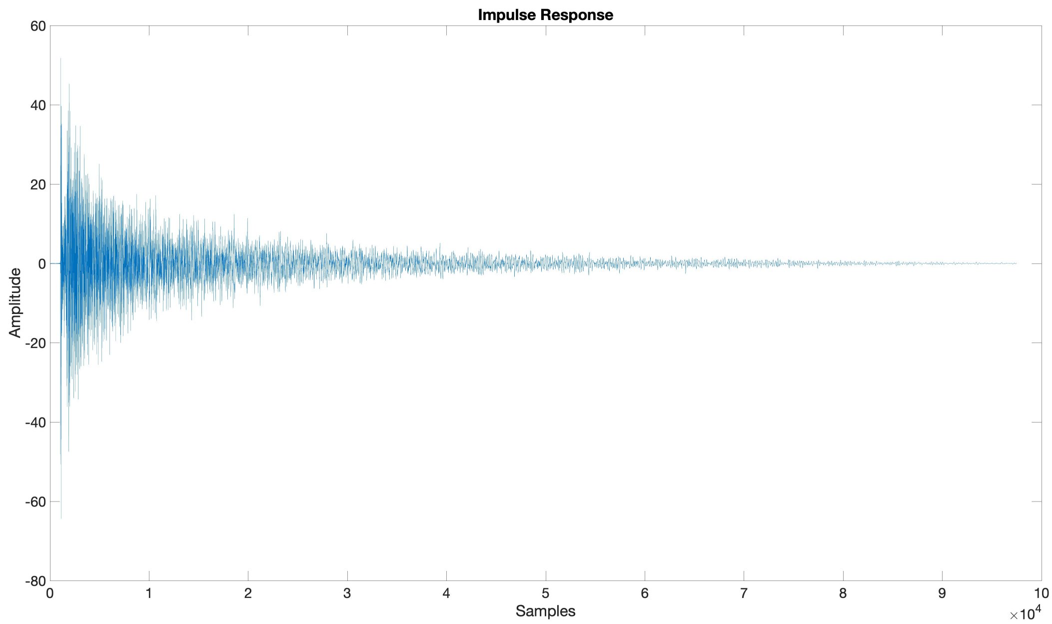

Figure 8: An example of an impulse response

An impulse response contains all the necessary information to then calculate other useful parameters for room acoustics, particularly reverberation time and the Speech Transmission Index (STI).

2.3.3 Reverberation Time

Sound can be split into two categories: direct and indirect sound. Direct sound is any sound wave that travels from the source to the receiver in one straight path. Environments where direct sound is the only sound present are called free field environments. Open spaces in nature are considered to be free field conditions, if the ground material does not contribute significant reflections. Anechoic chambers are designed to create artificial free field conditions by eliminating reflections off the floor, ceiling, and walls.

Indirect sound groups every sound that is not traveling from the source to the receiver in a straight path: this includes reflections (one or many) and refractions, and is referred to as reverberation. Reverberation itself is split into early reflections and late reverberation. These are shown in Figure 9.

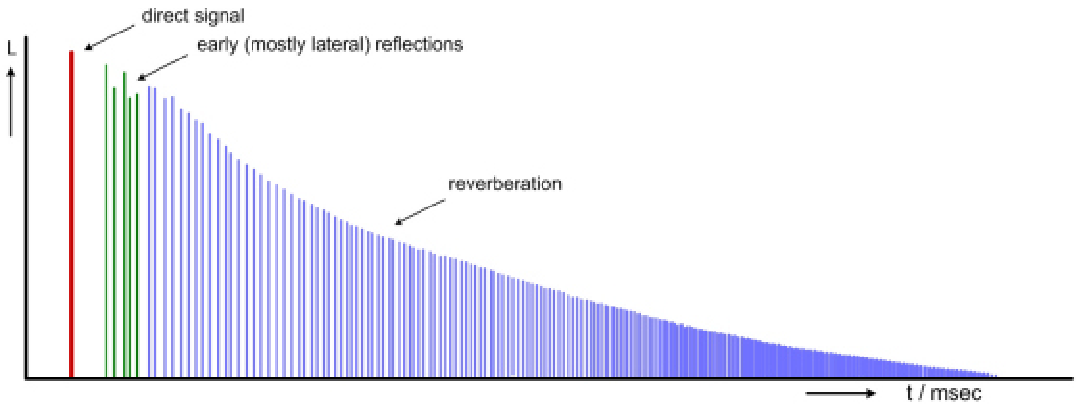

Figure 9: Early reflections and late reverberation. Reprinted from [30]

The time value that separates the two definitions is debated, but a classical reference value is 80 ms [31]. This is based on the Precedence Effect, which states that two sounds occurring within a certain short period of time will be perceived as simultaneous by the listener. Research has shown that the upper limit of time difference varies by type of sound, and is around 50 ms for speech, and 100 ms for music [32].

In order to analyze the amount of reverberation present in a space, reverberation time, T_{60}, is used. T_{60} is defined as the time it takes for a sound to reduce by 60 dB SPL. Reverberation time can be computed if the surface area and surface materials of a room are known through the Sabine formula.

$$T_{60} = \frac{0.049V}{a} \tag{8}$$

where V is the total room volume and a is the total room absorption at a specific frequency. a is calculated by summing the multiplication of the surface area of each individual material by its sound absorption coefficient. The absorption values have

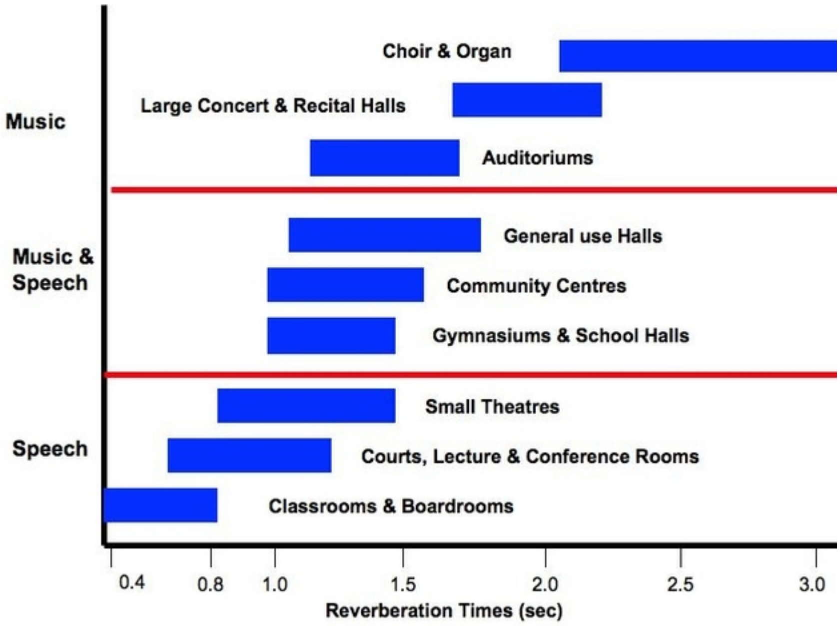

Figure 10: Typical reverberation times of common spaces. Reprinted from [33]

been found experimentally and can be easily found online. Typical reverberation times for different spaces are shown in Figure 10.

However, finding a comprehensive list of the surface areas and absorption coefficients of all the materials in an entire room can be time consuming, and the values found from reference charts will differ, even if slightly, from the real values of the room under test due to factors such as damage or deterioration of the materials over time.

A more accurate way of calculating reverberation time is through a room's impulse response. Additionally, this does not require any knowledge of the composition of the room. M. R. Schroeder introduced this method in 1964 [34]. The impulse response is squared and then integrated backwards over its duration, starting from the point in which the impulse response and background noise are indistinguishable. This yields one curve that represents the level decay of the impulse in the room over time.

However, in some situations it is difficult to measure a 60 dB reduction in sound level, especially in very large rooms where the signal can get lost within the background noise level. T_{20} and T_{30} are two other parameters used, measuring the 20 and 30 dB reductions in SPL respectively. It is then possible to convert to T_{60} as shown.

$$T_{60} = 2T_{30} = 3T_{20} \tag{9}$$

It is necessary for the noise floor to be at least 10 dB below the T_{20} or T_{30} point in order to achieve valid results.

The reverberation time is then calculated by finding the time between the 5 dB and 25 dB decay points for T_{20}, or the 5 dB and 35 dB decay points for T_{30}. This -5 dB starting point is used to eliminate the effect of early reverberations on the calculated value. Figure 11 illustrates the process for finding T_{20} and T_{30}. Early reflections can be quantified using Early Decay Time (EDT), which expresses the time it takes for the signal to drop by 10 dB from its starting point.

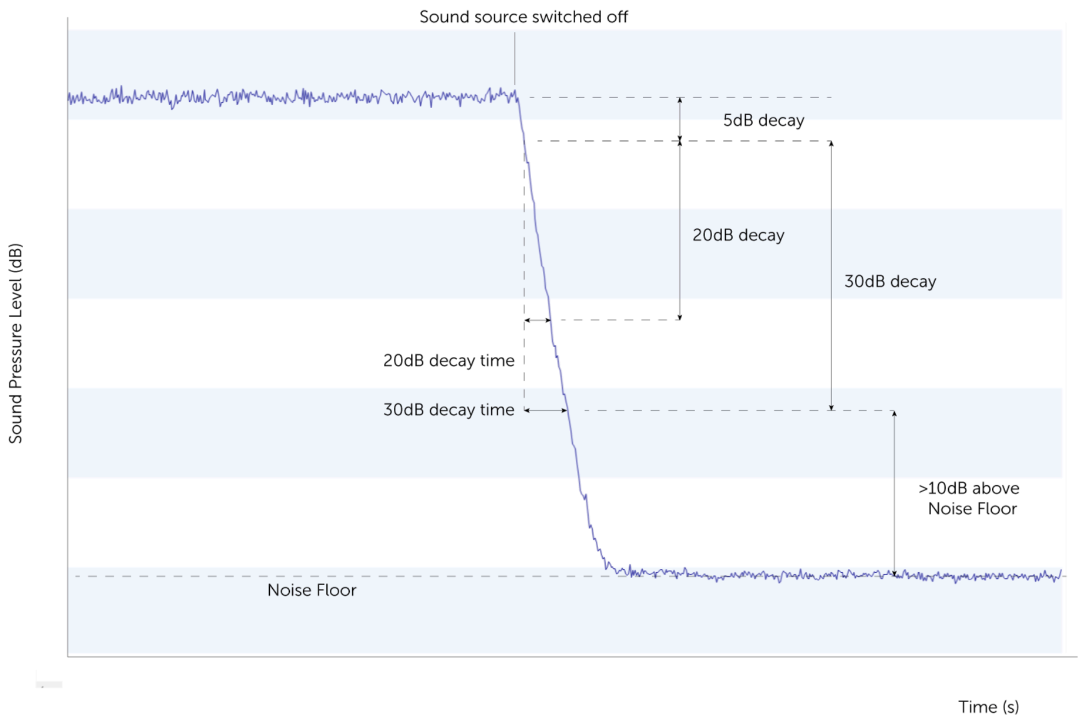

Figure 11: Reverberation time calculations. Reprinted from [35]

2.3.4 Speech Transmission Index

An important part of this thesis research is to evaluate how well people can understand each other within the sports hall environment. This is especially useful for group activities, where understanding teammates or instructors is crucial to good performance.

STI is a measure of how well speech is transmitted across a channel, which can take the form of a room or a telephone line, for example. STI is measured from 0 (bad) to 1 (excellent), and typically a value of at least 0.45 is considered fair for most situations. Figure 12 shows how intelligibility is dependent on STI for different types of speech signals.

Like reverberation time, STI can be calculated directly from the recorded impulse response of a room [36]. This is done through the Modulation Transfer Function (MTF), which is found by dividing the magnitude of the Fourier transform of the envelope spectrum of the impulse response, and subsequently dividing it by the total energy in the impulse response. The impulse response must be at least 1.6 seconds long, to allow for a frequency resolution of 0.63 Hz.

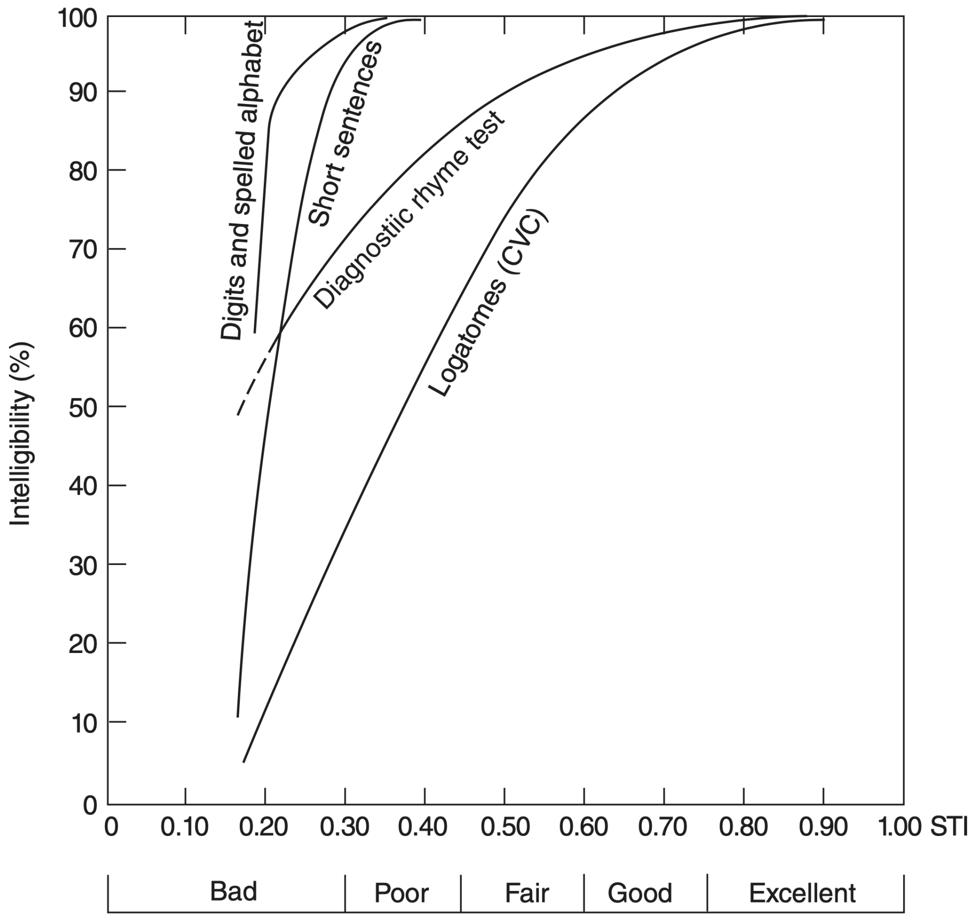

Figure 12: Relationship between STI and intelligibility. Reprinted from [37]

The impulse response is initially passed through seven octave filters, ranging from 125 Hz to 8 kHz (i.e., the frequency range of speech). Seven MTFs are therefore calculated. The next step is to find so-called modulation values: m-values. The amplitude of each MTF at 14 modulation frequencies (0.63, 0.79, 1, 1.26, 1.58, 2, 2.51, 3.16, 3.98, 5.01, 6.31, 7.94, 10, and 12.5 Hz) is found, resulting in a total of 98 m-values.

Each m-value is subsequently converted into an Apparent Signal-to-Noise Ratio (SNR_{app}), expressed in dB, using the equation below.

$$SNR_{app} = 10 \log_{10} \frac{m}{1-m} \tag{10}$$

The range of apparent SNR values is limited: any value below -15 dB is set to -15 dB, and any value above 15 dB is set to 15 dB. The mean apparent SNR value for each of the seven octave bands is also taken. The final single number quantity for the apparent SNR is calculated by using a weighted average. The weights for each octave band are shown in Table 1.

Frequency /Hz	125	250	500	1000	2000	4000	8000
Weight	0.13	0.14	0.11	0.12	0.19	0.17	0.14

Table 1: Frequency weights for apparent SNR calculation

To obtain STI, the apparent SNR is converted using the following equation.

$$STI = \frac{SNR_{app} + 15}{30} \tag{11}$$

3 Methodology

This chapter outlines the methodology of both the measurement and calculation processes. The sports facilities that were investigated as part of the LIIKU project are introduced first. The requirements and practicalities are then explained by describing the legal regulations and standards that were used as a reference point. The equipment setup used for field measurements is then presented, along with the thought process behind the method for gathering data. The sports facilities are grouped in a handful of categories and category-specific measurement procedures are then detailed. Finally, the methods using for extracting results from measured data are explained.

3.1 Measurement Locations

14 sports facilities around the Helsinki metro area were selected as part of the scope of the LIIKU project. Four facilities were located in Helsinki, five in Espoo, four in Vantaa, and one in Kerava. 12 of the facilities were public complexes, and two were school gymnasiums. A total of 18 halls were selected for the acoustic measurements, as some facilities contained two similar spaces. Table 2 lists the facilities and provides a short description of the halls chosen to be measured within each one. Figure 13 shows the locations of the facilities on a map.

Name	Location	Built in	Description
Maunulan liikuntahalli	Helsinki	1998	Underground shelter, Sali 1, multisport court
			Underground shelter, Sali 2, handball court
Latokartanon liikuntahalli	Helsinki	2008	Sali 1, multisport court
			Sali 2, multisport court
Liikuntamylly	Helsinki	1980	Basketball/floorball court
Töölön kisahalli	Helsinki	1935	A-halli, basketball court
		1950	B-halli, basketball stadium with bleachers
Tuulimäen liikuntatilat	Espoo	1980s	Underground shelter, gymnastics hall
Leppävaaran liikuntahalli	Espoo	1991	Multisport court with bleachers
Tapiolan urheiluhalli	Espoo	1974	Basketball stadium with bleachers
Tapiolan koulu ja lukio	Espoo	2016	School gymnasium, multisport court
Otahalli	Espoo	1948	Multisport court with a balcony area for gym equipment
Rajakylän tenniskeskus	Vantaa	1994	Floorball court
Myyrmäen urheilutalo	Vantaa	1974	Multisport court with bleachers
Hakunilan kalliosuoja	Vantaa	1970s	Underground shelter, floorball court
Kanniston koulu	Vantaa	2011	School gymnasium, multisport court
Keravan uimahalli	Kerava	2019	‘Joona’ hall, yoga studio
			‘Olavi’ hall, small games room

Table 2: Sports halls chosen for measurement

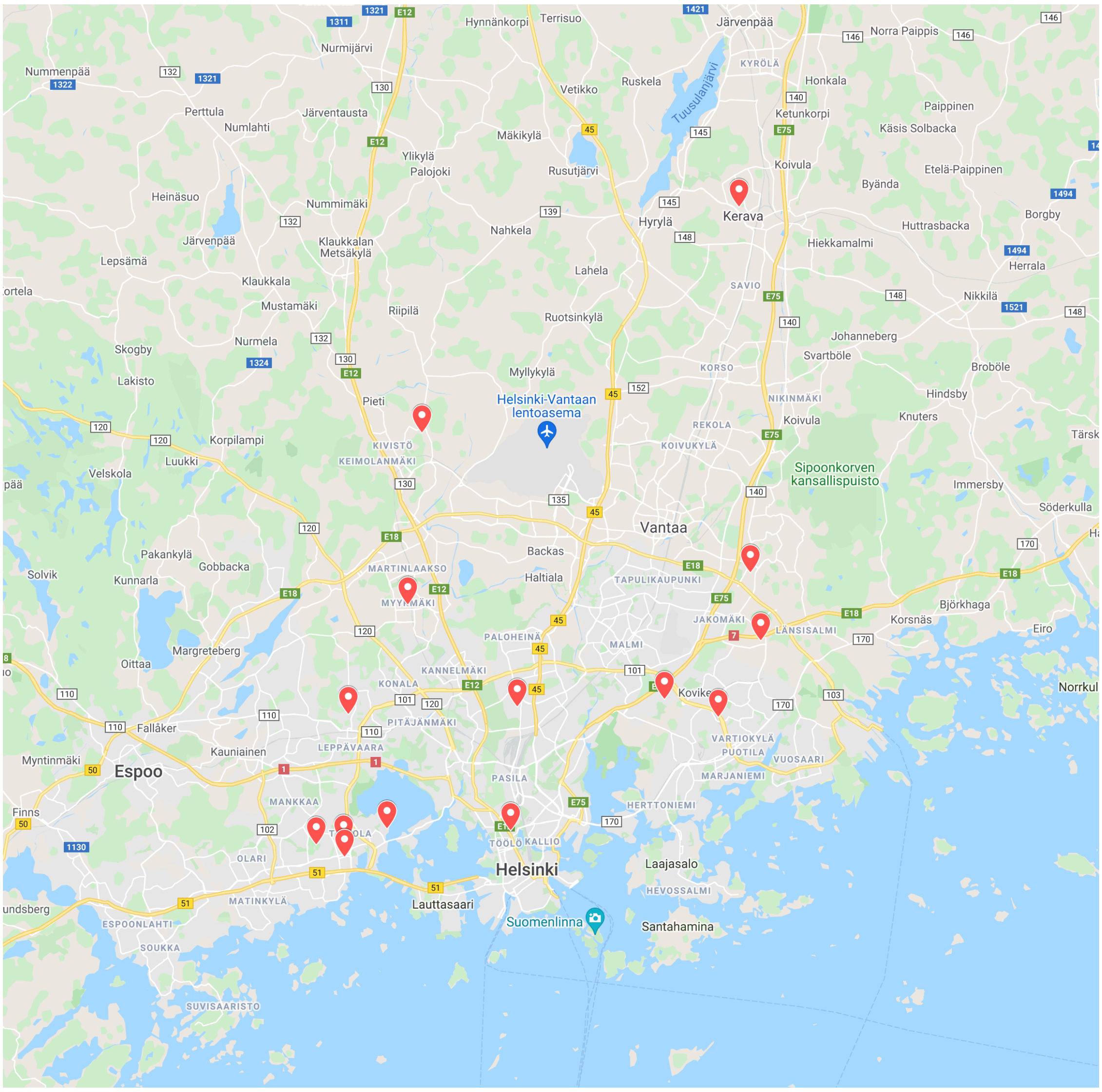

Figure 13: Locations of sports facilities, indicated by red markers, in the Helsinki metro area

3.2 Requirements & Practicalities

3.2.1 Finnish Regulations

As mentioned in the previous chapter, not much regulation specifically regarding sports hall acoustics is available. This thesis will use the RIL-243-2-2007 regulation [8] as well as the Decree 796/2017 of the Finnish Ministry of the Environment [17] as the primary reference values for the discussion of results. The limit values from these two regulations are shown in Table 3 and Table 4 respectively.

	Class A and B	Class C
Ceiling height below 5 m	< 1.1 s	< 1.5 s
Ceiling height above 5 m	< 1.3 s	< 1.9 s

Table 3: Reverberation time limits for RIL-243-2-2007

These values are to be satisfied for each octave band ranging from 250 Hz to 4 kHz. The 125 Hz octave band can exceed the values by up to 50%.

	T_{60}	STI
Canteen, sports hall (≤ 1500 m^3)	≤ 1.2 s	≥ 0.6

Table 4: Reverberation time and STI limits for Decree 796/2017

This scope of this regulation is extremely narrow, as the majority of sports halls exceed the volume limit. In fact, only the halls in Kerava were small enough to fit under this figure. Octave band requirements are not mentioned. It is assumed that they would be similar to the ones for the RIL regulation.

Other countries' regulations were also found, however they will not be considered as all of the sports halls included in this thesis are under Finnish jurisdiction.

3.2.2 Standards

There are currently no measurement standards that outline procedures specifically for sports facilities. The measurements carried out as part of this thesis followed procedures from both ISO 3382-1 and ISO 3382-2 [38]. These two standards explain the measurement procedures for room acoustic parameters in performance spaces and ordinary rooms respectively. ISO 3382-2 provides information about the number of source-microphone positions required, and ISO 3382-1 offers further guidance about the placement of the microphone around the room.

3.3 Field Measurements

In order to obtain results for the three parameters of interest (reverberation time, STI, and weighted noise level), two different sets of measurements needed to be undertaken. Reverberation time and STI can be extrapolated from recorded impulse responses, whereas weighted noise level is calculated in real time when using a sound level meter with a frequency analyzer.

The field measurements were undertaken at different times, due to the environmental requirements of each: impulse response measurements have to be done with empty and silent rooms, whereas noise level measurements require a normal level of activity within the room in order to provide a set of data that accurately reflects an everyday scenario.

The impulse response measurements were undertaken first due the Finnish government restrictions, imposed at the beginning of the year in response to the Covid-19 pandemic, that prohibited the use of indoor sports facilities with a very small number of exceptions, such as for professional athletes.

The noise level measurements were carried out once restrictions had been relaxed. Not all facilities could be visited for these measurements, as the situation was not yet back to pre-Covid levels. As a result, it was decided to not gather data from all 14 facilities, since a suitable accurate scenario was very difficult to achieve under the circumstances. Viewers were still not allowed for events such as practice sessions and matches, and some facilities did not allow viewers of any kind, even if for measurement purposes.

The main parameter of interest from the noise level measurements was A-weighted equivalent noise level, L_{Aeq}. As stated in the previous chapter, A-weighting is designed to represent sound levels in a way that accurately reflects the human auditory perception. Equivalent noise level, L_{eq}, is a single number quantity most commonly used to quantify a sound source over a period of time. As sound source levels vary over time, the L_{eq} value represents the total energy of the recorded sound as if it were a constant source operating at that dB value. It is important to note that this is not a measure of average sound level over time.

3.4 Equipment Used

3.4.1 Noise Level Measurements

The noise level measurements had a simple setup, only consisting of a hand-held microphone and analyzer combination device. The model used was the B & K Type 2250-S hand-held analyzer kit with a B & K 1/2" free-field microphone (shown in Figure 14). The kit was used in advanced frequency analyzer mode, which records input data into one-third octave bands from 20 Hz to 20 kHz, and also calculates parameters such as L_{Aeq}.

Figure 14: B & K type 2250-S analyzer with 1/2" free-field microphone. Reprinted from [39]

3.4.2 Impulse Response Measurements

The impulse response measurements were carried out with a source-receiver system. As detailed in ISO 3382, the sound source needs to be as omnidirectional as possible, with minimal directivity across octave bands with a pink noise signal. The source used for the measurements was the 01dB LS01 omnidirectional noise source, which features a dodecahedron loudspeaker, and is manufactured to ISO 3382 specification. The receiver was a G.R.A.S. Type 46AF 1/2" free-field microphone. This microphone exhibits an almost flat frequency response across the frequency range of interest. It has a ± 1 dB deviation between 5 Hz and 10 kHz, and a $\pm$ 2 dB deviation between 3.15 Hz and 20 kHz. A G.R.A.S. 12AQ power module was used to power the microphone using LEMO cables.

The excitation signal chosen for these measurements was a logarithmic sine sweep (20 Hz to 20 kHz) with a three second duration, generated using MATLAB. A laptop running REAPER software, connected to a RME Fireface UCX interface, was used to send and receive signals. The equipment used is shown in Figure 15, and a diagram of the measurement setup is shown in Figure 16.

In order to assure the highest signal-to-noise ratio possible, the input signal was amplified just below clipping level within REAPER. During the measurements, this level was adjusted with microphone distance (i.e., lowered when the microphone was close) in order to avoid clipping on the microphone side as well. The sampling rate was set to 48 kHz.

Figure 15: Impulse response measurement equipment. From top left, clockwise: LS01 source, 46AF microphone, UCX interface, and 12AQ power module. Reprinted from [40, 41, 42, 43] respectively

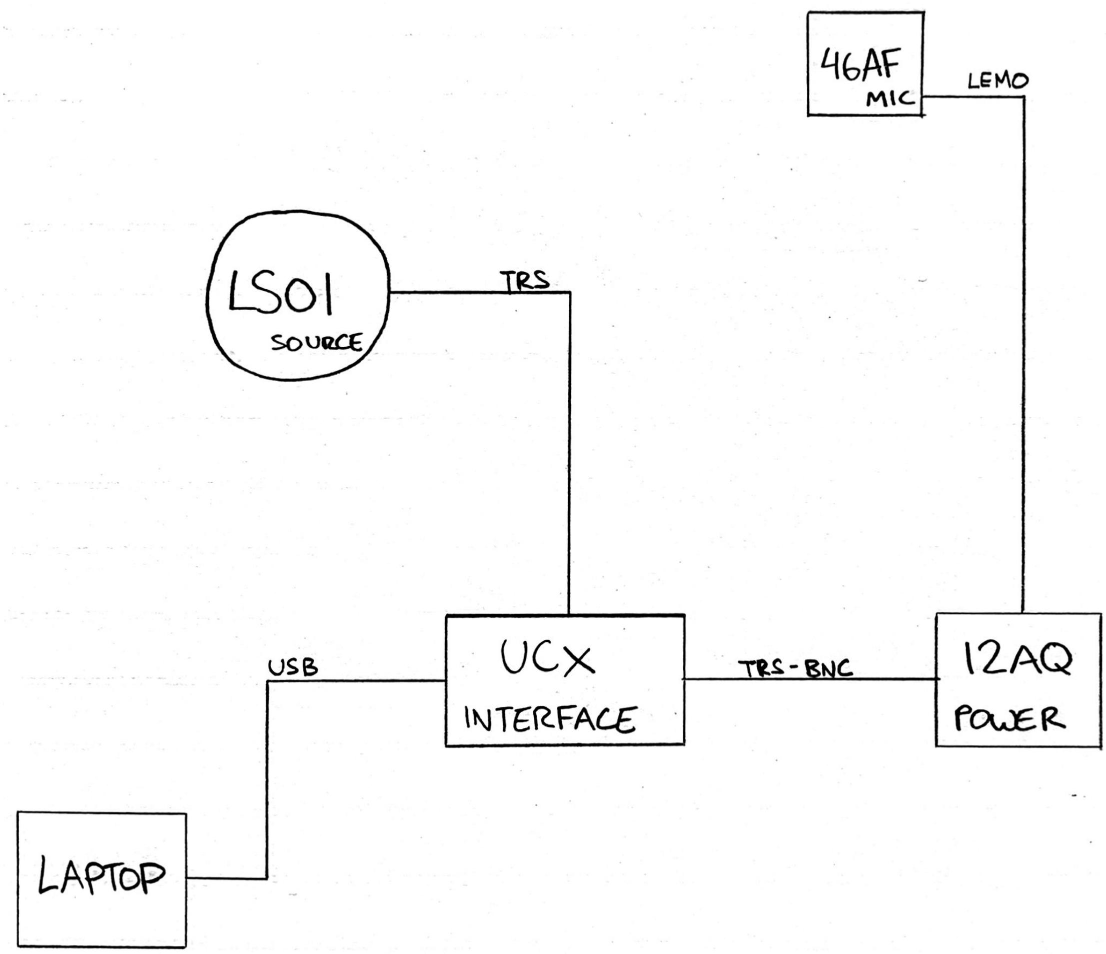

Figure 16: Impulse response measurement equipment setup, including cable connections

3.5 Measurement Positions

In this section, the chosen measurement positions of source and receiver are explained. The impulse response measurements followed the ISO standards and a set of rules designed to make the procedure more efficient, as well as to facilitate comparison of results. The noise level measurement positions, explained at the end of this section, were dependent on the location and event that was being measured.

In order to adhere to the standards presented previously, certain impulse response measurement procedures had to be adopted. The number of source-receiver combinations was chosen to be nine, with three distinct speaker positions, and three corresponding microphone positions for each one. This follows the engineering method in ISO 3382-2.

Microphone positions were made sure to be at least 2 m apart from each other, at least 1 m away from a surface, and also not close enough to the speaker in order to make sure that the direct sound was not dominating the recording. Speaker height was set to 1.5 m. ISO 3382-1 states that microphone height should be 1.2 m to represent ear height of seated listeners in rooms for speech and music. This was followed for relevant positions, such as in bleachers, but the microphone was positioned higher in locations where it represented basketball players on the court, for example.

In order to provide the most solid basis possible for comparison between locations, the halls were grouped into three distinct categories:

- Category 1: multisport court with space for viewers;
- Category 2: multisport court without space for viewers;
- Category 3: anything outside of categories 1 and 2.

The measurement procedures, particularly regarding the position of equipment in the space, were planned to be as similar as possible to each other when measuring halls within the same category. As a result, the difference in measured values can be almost wholly attributed to the acoustics of the room itself.

3.5.1 Category 1

Category 1 includes halls that contain a multisport court, but no space for viewers. In this case, there is minimal space between the court lines and the walls, typically less than 2 m. Multisport courts are designed to be used for a variety of different indoor sports, such as basketball, futsal, handball, and floorball.

The lines for basketball were used as reference points to determine the positions of both the speaker and the microphone. This allowed for a 'standardized' set of measurement positions across halls in this category, which is especially useful for STI data, as it is heavily influenced by distance.

As stated in ISO 3382-1, source positions should be located where sound would be usually coming from under normal use circumstances, and microphone positions

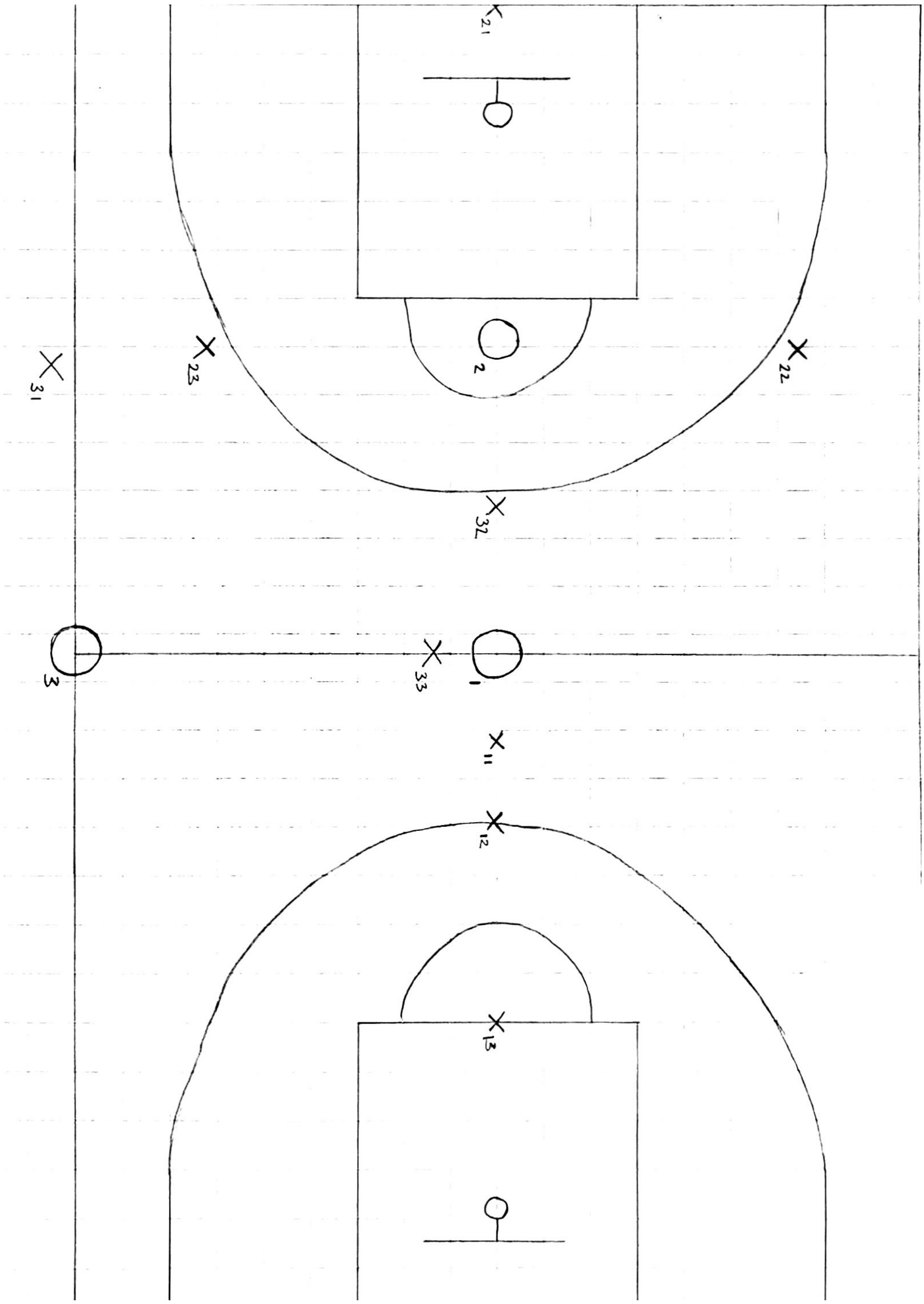

Figure 17: Measurement positions for Category 1 halls

should be located where an audience would be listening from. A diagram of the speaker and microphone positions on the basketball court is shown in Figure 17.

The circles represent the speaker, and the X symbols represent the microphone. The subscripts are used to identify source-receiver combinations, where the first number is the source position, and the second one is the microphone (i.e., X_{12} indicates that this is the second microphone position for the first speaker position).

The speaker positions were chosen to mimic the most important sound sources in the context of a basketball game. The first one is in the middle of the court, the second one is at the top of the key in one half, and the third one is on the sideline halfway across the court. The first position is as far away from any boundary as possible, and is also where the game always passes through, as players run up and down the court. The second position is also significant in a game context, as a majority of game time is spent in this area (on either side of the court), therefore most of the voices and impact sounds will come from here. The third speaker position, on the sideline, is used to represent coaches and bench staff during a game.

The microphone positions were chosen both to mimic significant listener positions within the hall, as well as to provide a solid basis for STI data. The first set of positions are progressively farther from the source in a straight line, parallel to the sidelines. The second set of positions represents players on the court, two wing players on the 3 point line, and one player under the basket. The third set of microphone positions is used to represent both bench players, as well as active players, using a hypothetical coach as the source.

Table 5 gives more detail on each source-receiver combination.

Source-receiver combination	**Microphone distance from source /m**	**Hypothetical listener**
11	3	N/A
12	6	N/A
13	8	N/A
21	6	Low post player / referee
22	4	Wing player
23	4	Wing player
31	6	Bench player
32	10	Playmaker
33	8	Playmaker

Table 5: Category 1 measurement positions

Some of the halls in this category did not function as basketball courts, therefore the lines were not drawn on the floor. This was the case in Maunula's Sali 2, Rajakylä, and Hakunila. Maunula's Sali 2 was a handball court, and the measurement positions were interpreted in a similar way to the basketball lines (i.e., a center court position, an attacking position, and a sideline position). The same was done for Rajakylä and Hakunila, which had floorball courts.

3.5.2 Category 2

Category 2 includes halls that contain a multisport court and space for viewers. This can be in the form of bleachers or extra space outside of the court lines for people to stand in. The thought process behind the measurement positions is the same as for Category 1, but the third speaker position has different microphone positions associated to it, and varies from hall to hall.

The microphone positions for the third speaker position were placed to represent the audience for a sporting event. In the case of a hall with bleachers, such as in the Tapiolan urheiluhalli, the microphone was placed midway up the bleachers, to represent an average viewer. The three positions would then be directly in front of the speaker, as well as to both sides. This is shown in the diagram in Figure 18.

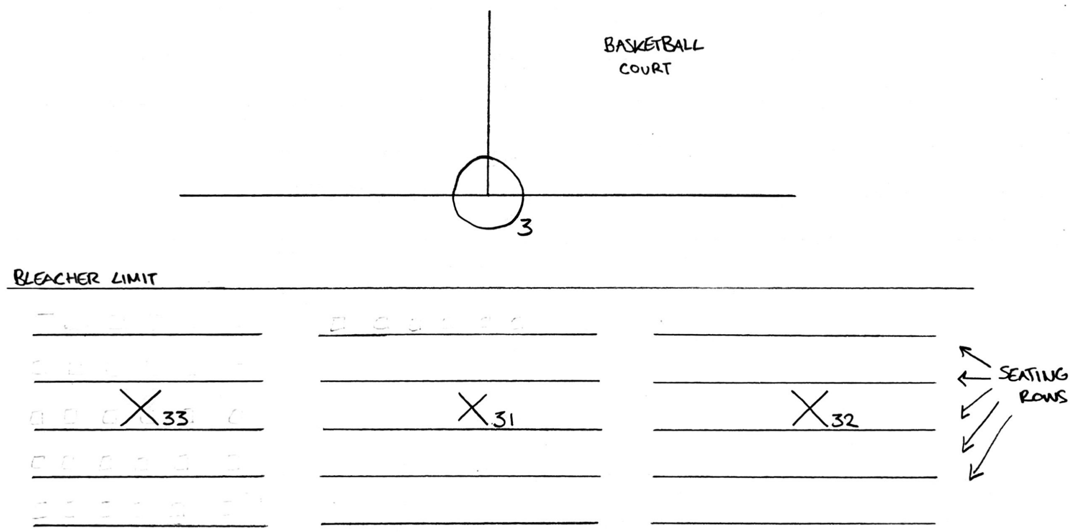

Figure 18: Modified third measurement position for Category 2 halls

3.5.3 Category 3

Category 3 includes halls that do not meet the characteristics of the previous two categories. In this study, only two facilities were different from the rest, namely the ones in Tuulimäki and Kerava, for a total of three halls.

The Tuulimäki hall had some characteristics in common with the other categories, but its intended purpose is what caused it to be differentiated from them. As it is an underground shelter, it is a similar space to Hakunila and Maunula, with tall concave rock ceilings. However, this hall is used for gymnastics, and therefore contains a significant amount of softer materials in the form of flooring or gymnastics equipment (e.g., mats and foam pits), compared to the hard flooring used for a majority of team sport applications. The difference in material, as well as in hall shape and purpose, significantly affected the thought process behind microphone placement, and it is for this reason that the Tuulimäki hall was included in Category

3. The microphone distances are shown in Table 6, and a diagram of the speaker and microphone positions used in this hall is shown in Figure 19.

Source-receiver combination	**Microphone distance from source /m**
11	3
12	5
13	7
21	5
22	3
23	7
31	5
32	3
33	9

Table 6: Microphone distances in Tuulimäki

The Kerava halls were included in this category due to their size in comparison with all the other facilities, as well as their different purpose. The two spaces are significantly smaller, with lower ceilings, and therefore were expected to produce different results. As mentioned previously, the two spaces are also the only ones that conform to the 1500 m^3 limit described in [17]. The measurement approach for this location was slightly different, as three speaker positions were deemed unnecessary for the limited floor area. It was decided to use two speaker positions and four microphone positions for each space instead. The microphone distances are shown in Table 7, and a diagram of the speaker and microphone positions used in this hall is shown in Figure 20.

Source-receiver combination	**Microphone distance from source /m**	
	'Joona'	'Olavi'
11	7	8
12	5	11
13	6	8
14	9	5
21	4	4
22	7	9
23	10	9
24	13	4

Table 7: Microphone distances in Kerava.

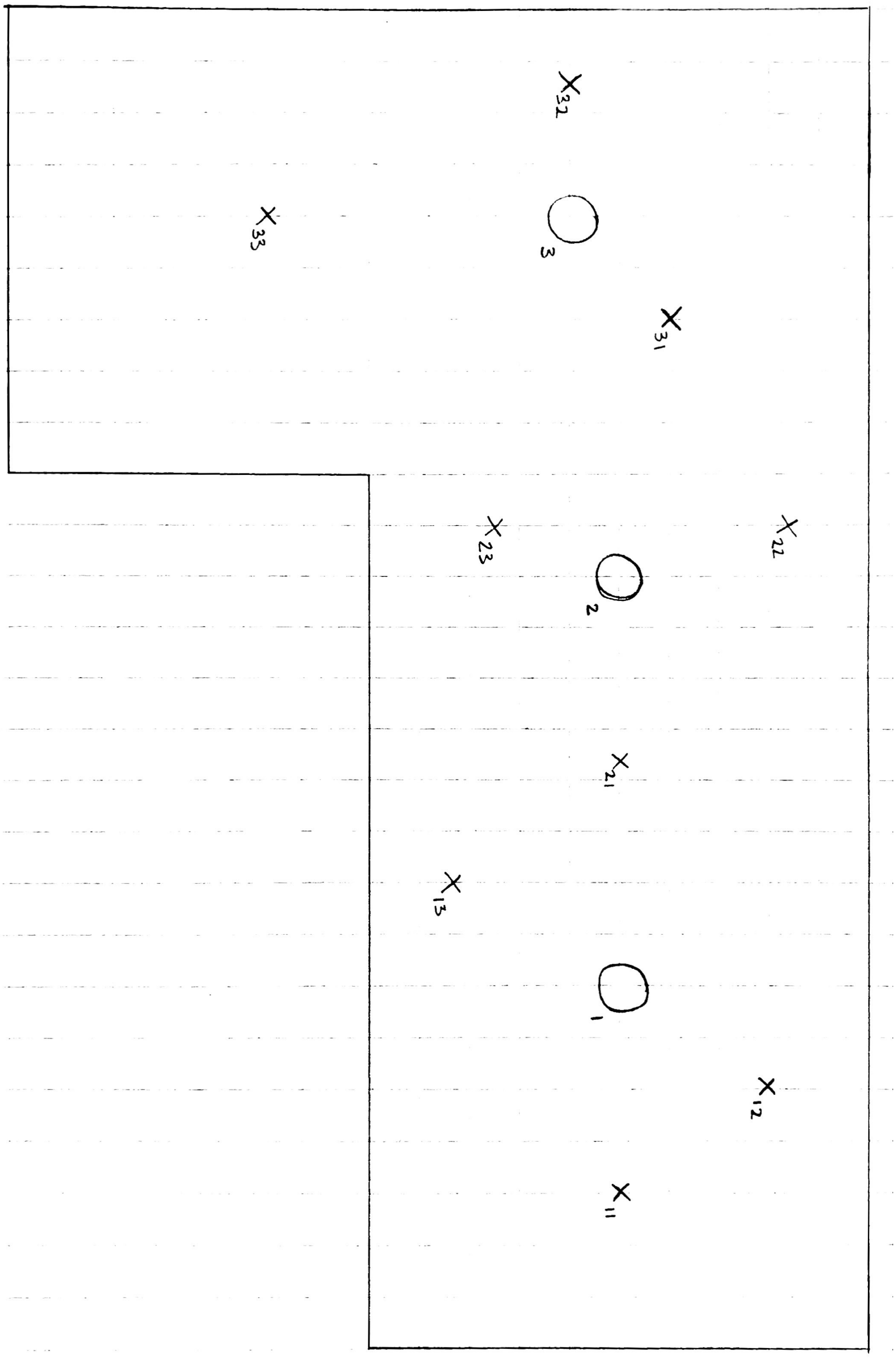

Figure 19: Measurement positions for Tuulimäki

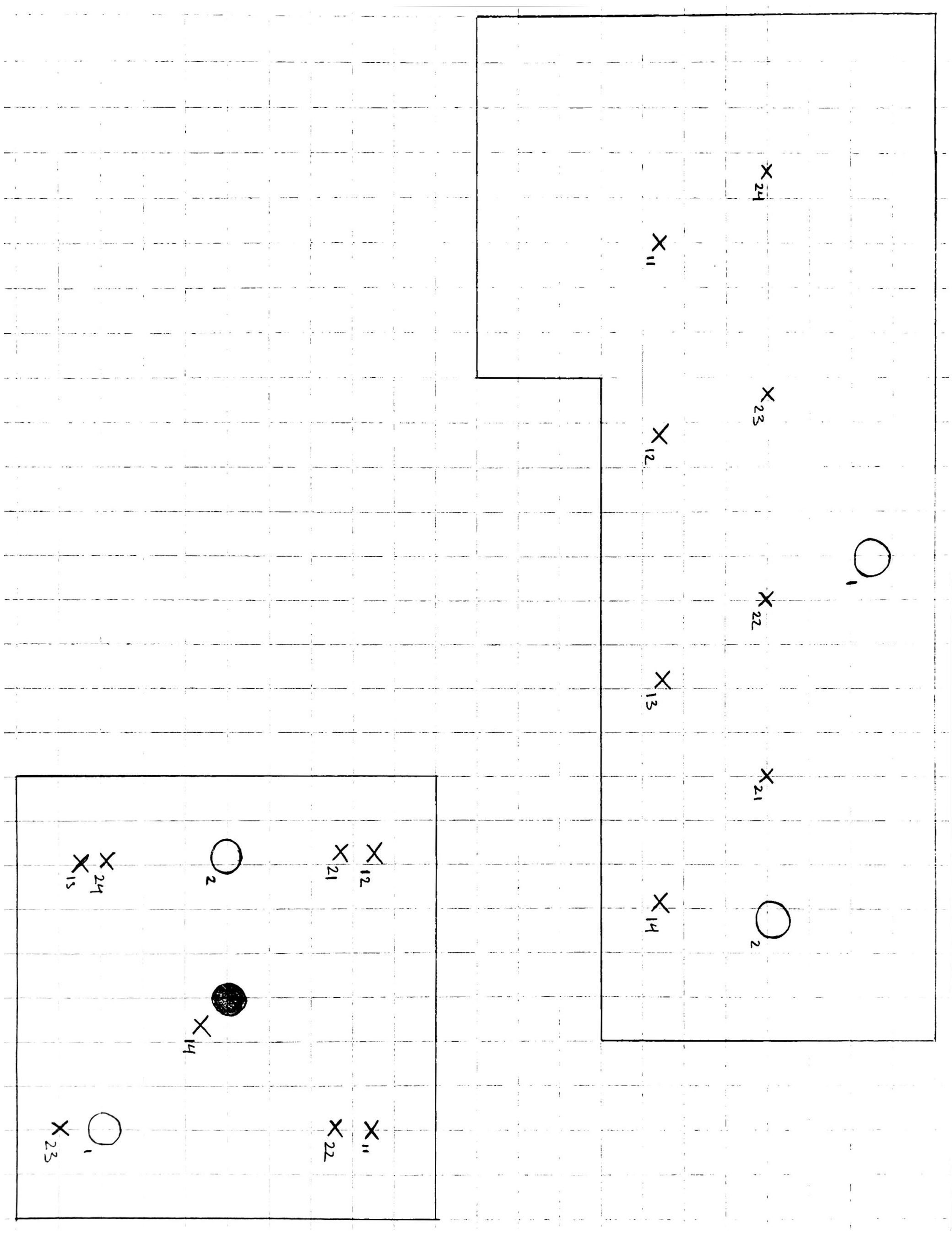

Figure 20: Measurement positions for Kerava. The colored in circle represents a column

3.5.4 Noise Level Measurements

Due to the nature of the measurement procedure for noise levels, the chosen positions did not follow a set of standardized rules like the impulse response measurements did. Different factors could affect how the measurements were being carried out, such as the event under test, the age group involved in the event, as well as the type of hall being measured. These factors, as well as other relevant details, are laid out in table 8 for each of the halls that was able to be measured for noise levels.

Hall name	Hall type	Event	Age group	Noise sources	Notes
Latokartano Sali 1	Multisport court	Gymnastics class	Elementary school	Voice, music, impact	Gymnasium divider lowered
Tapiolan urheiluhalli	Basketball stadium	Basketball practice	U19 (2003-04)	Voice, impact	
Otahalli	Multisport court	Floorball practice	Middle school	Voice, impact	Measurements taken from gym balcony, weightlifting sounds also present
Myyrmäki	Multisport court with bleachers	Handball practice	Elementary school	Voice, impact	
Tuulimäki	Gymnastics hall	Gymnastics class	Elementary/middle school	Voice, impact, music	Multiple classes simultaneously occurring
Tapiolan koulu ja lukio	School gymnasium	Sports class	Elementary school	Voice, impact	Gymnasium divider lowered

Table 8: Noise level measurement location details

However, certain aspects of the measurement procedure, such as microphone height, were decided using the Acoustics & Noise Consultants (ANC) Guidelines for June 2020 [44] as a reference.

The microphone was placed on a stand at a height of 1.5 m, at least 1 m away from surfaces, and was always made sure to be 1.5 m away from sound sources such as vents or windows. The ANC guidelines also specify a number of measurement positions based on the floor area of the space. These are shown in table 9.

Floor area /m^2	Measurement positions
≤ 25	1
25 - 99	3
100 - 499	6
≥ 500	10

Table 9: ANC measurement position guidelines. Adapted from [44]

These guidelines were only able to be followed in the case of the Tapiolan urheiluhalli, where 10 measurement positions were used. In the other cases, the measurement position guidelines were unable to be followed mainly due to a limited viewer area, such as in the case of Otahalli, or limited court accessibility (i.e, not being able to place equipment on the court to avoid the disruption of activities).

The noise level in each microphone position was recorded for a duration of two minutes.

3.6 Data Processing

In this section, the procedures for extracting results from measured data are explained. MATLAB was used for all of the data processing.

3.6.1 Noise Level Measurements

The frequency analyzer used to record noise level data calculated relevant parameters, such as L_{Zeq} and L_{Aeq}, in real time. The data was transferred to a computer using an SD card and the B & K software. The numbers were subsequently extracted into Excel in order to calculate L_{Aeq} in one third octave bands, as the analyzer only gave L_{Zeq} in one third octave bands and L_{Aeq} as a single number average over every band. In Excel, A-weighting was applied to the L_{Zeq} values to convert them into L_{Aeq} values.

Each measurement position's L_{Aeq} data was loaded into MATLAB, and each hall's set of data was averaged to produce a single value for each octave band. Decibel values must be converted into linear values before arithmetically averaging, and then reconverted into dB, as an arithmetic average of dB values is equivalent to a geometric average of linear values.

The results for the noise level measurements are presented as bar graphs, with one third octave bands on the x-axis, and L_{Aeq} values on the y-axis. The single number quantity for L_{Aeq} is calculated by taking the linear sum of all octave band L_{Aeq} values and converting it into dB.

3.6.2 Impulse Response Measurements

The recorded data from the impulse response measurements was in the form of audio files that contained the original excitation sine sweep modified by the environment it was played in. In order to calculate reverberation time and STI values, the impulse response of the room needs to be extracted from the recorded signal. The method introduced by Farina [45] was used to achieve this.

A simple single input-output system can be described in the time domain by the following equation.

$$y(t) = x(t) \circledast h(t) + n(t) \tag{12}$$

Where $y(t)$ is the output being generated by the convolution of the input $x(t)$ and the system's transfer function $h(t)$. Noise, $n(t)$, assumed to be white Gaussian and uncorrelated to $x(t)$, is produced as well. In the context of this thesis, $x(t)$ is the speaker signal, $h(t)$ is the room's impulse response, and $y(t)$ is the signal recorded by the microphone.

One way to isolate the impulse response would be to convert the equation into the frequency domain using the Fourier transform, as the convolution operation becomes a simple multiplication, and $h(t)$ be calculated easily.

$$Y(f) = X(f)H(f) \rightarrow H(f) = \frac{Y(f)}{X(f)} \tag{13}$$

$h(t)$ is then found by using the inverse Fourier transform. The noise function is assumed to cancel out as a result of the averaging of many measurements.

Due to the fact that the Fourier transform is a periodic process, the convolution and deconvolution processes are inherently periodic as well (i.e., circular convolution). This can cause time aliasing, which leads to distortion issues in the impulse response. Distortion can also appear due to a system's nonlinearities. In the case of a loudspeaker, these usually appear for a very short time at the start of operation, as the system reaches its steady state.

Farina states that using a logarithmic sweep as an input signal causes these nonlinear distortion peaks to appear clearly, and proposes a method for separating them from the impulse response. Instead of using circular deconvolution in the form of an inverse Fourier transform, linear deconvolution in the form of an inverse filter of the input, $f(t)$, is applied in the time domain.

$$h(t) = y(t) * f(t) \tag{14}$$

This causes the impulse response to be separated from the output, with its linear part starting at the end of the inverse filter. The distortion peaks will appear before the linear response.

Since the input sweep for the measurements was three seconds long, so is the inverse sweep, and therefore the measured linear impulse response starts at that point as a result of the convolution operation. This is shown in Figure 21.

The response shown above is a single measurement position. There are two clear distortion peaks on the left side of the zoomed graph, just after the 130000 sample point. The linear impulse response starts at 144000 samples, as this corresponds to three seconds using the 48 kHz sampling rate, and is shown by the vertical line at that point.

In this specific case, there is an approximately 1000 sample delay between the 144000 sample point and the actual start of the impulse response, corresponding to around 20 ms. This can be attributed to the time it takes for the stimulus signal to travel from the speaker to the microphone. The microphone was positioned 8 m away from the speaker. Assuming the speed of sound to be 343 m s^{-1}, it would take around 23 ms for the signal to travel this distance.

The next step is to window each impulse response in order to obtain only the linear part. As mentioned previously, the starting point for each response is at 144000 samples. The end of the impulse response, also referred to as the reverberant tail, was found manually by looking at each response plot. The end point is where the impulse response and background noise are indistinguishable from each other. The impulse responses are now completely extracted and can be manipulated to find reverberation time (T_{60}) and Speech Transmission Index (STI). The STI calculation method is described in Chapter 2.3.4.

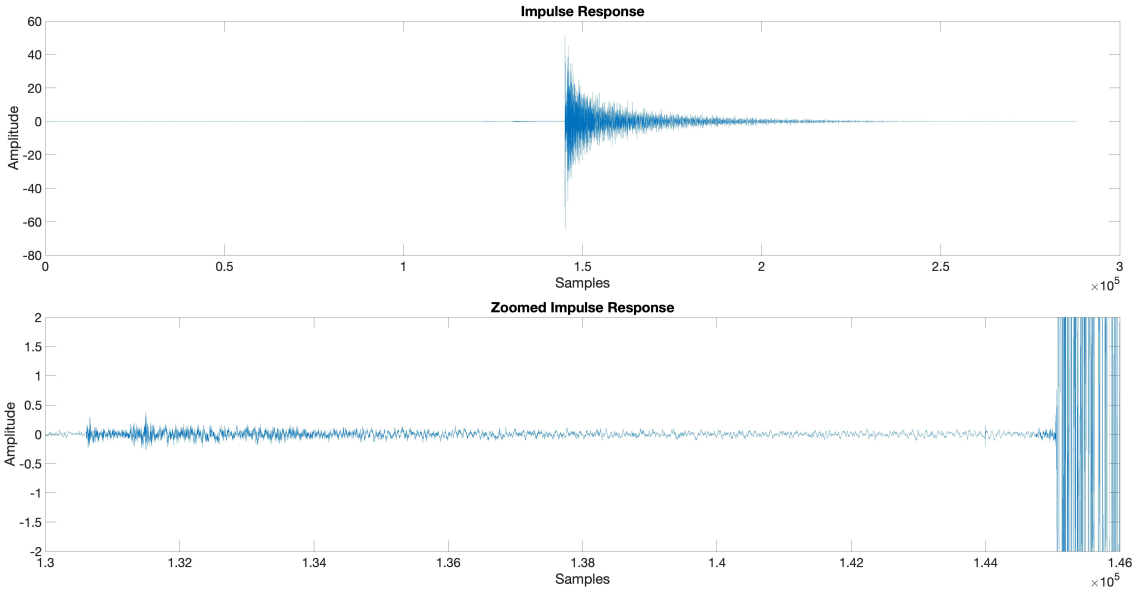

Figure 21: Measured impulse response (top) with distortion peaks shown (bottom)

The Schroeder integral method was used to calculate T_{60}. The impulse responses are initially filtered through one third octave band filters (125-8000 Hz bands), then squared and integrated backwards to create the Schroeder curves, which are normalized and converted into dB. Due to differences in Signal-to-Noise Ratio (SNR) across facilities, T_{60} was extrapolated from T_{30} calculations. The -5 and -35 dB points are found, and the x-axis difference between them is consequently the T_{30} value. This is converted into seconds and finally doubled to obtain the T_{60} values.

There are 19 curves for every measurement position: one for each octave band. The T_{60} values were averaged for each octave band across measurement positions. The results are presented as line graphs, with one third octave bands on the x-axis, and T_{60} values on the y-axis.

Examples of the presentation of recorded data are shown in the next chapter.

4 Results

This chapter presents the results obtained from the measurements.

All of the halls are initially evaluated against the acoustic regulations presented in the previous chapter. The results are then split into two categories, and presented in more detail. The two result categories are as follows.

- Recorded data;
- Computed data;

Recorded data includes the noise level measurements as the results did not need any further processing after recording, except a simple conversion from Z-weighted to A-weighted levels.

Computed data includes all results that have been extrapolated from the recorded data through MATLAB processing. The two parameters in this category are reverberation time (T_{60}) and Speech Transmission Index (STI).

4.1 Evaluation against Regulations

Table 10 lists all of the measured halls and states whether they meet the RIL and Environment Ministry Decree regulations or not.

Hall Name	Compliant with RIL?	Compliant with Decree 796?
Hakunila	No	N/A
Kannisto	No	N/A
Kerava 'Joona'	Yes (C class)	T_{60} yes / STI no
Kerava 'Olavi'	Yes (A/B class)	Yes
Latokartano Sali 1	No	N/A
Latokartano Sali 2	No	N/A
Leppävaara	No	N/A
Liikuntamylly	Yes (C class)	N/A
Maunula Sali 1	No	N/A
Maunula Sali 2	No	N/A
Myyrmäki	Yes (A/B class)	N/A
Otahalli	Yes (C class)	N/A
Rajakylä	Yes (C class)	N/A
Tapiola	Yes (C class)	N/A
Tapiolan Koulu	No	N/A
Töölön Kisahalli A	No	N/A
Töölön Kisahalli B	No	N/A
Tuulimäki	Yes (A/B class)	N/A

Table 10: Sports hall evaluation against Finnish regulations.

The Decree 796 regulation only applies to the halls in Kerava, as they are the only spaces under the 1500 m^3 volume upper limit.

The results show that eight of the visited sports halls meet the RIL requirements. Graphical representations of these results are shown in section 4.3.

4.2 Recorded Data

As mentioned previously, restrictions due to the Covid-19 pandemic had a significant effect on the noise level measurements. Only six halls were visited for these measurements and only one of these can be considered to accurately represent an ordinary situation. Two examples are given in this section, to show the difference between a restricted scenario and a normal scenario.

4.2.1 Covid-19 Limited Scenario

The restricted scenario is from a basketball practice session in the Tapiolan urheiluhalli. There were 10 total measurement positions, both in the bleachers as well as on court level, outside the lines. The results are shown in Figure 22.

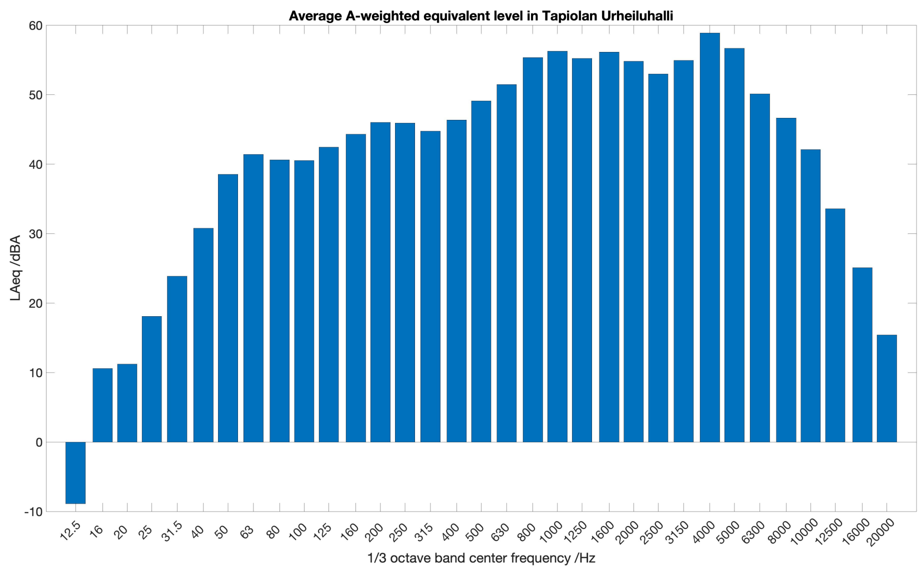

Figure 22: Average L_{Aeq} in Tapiolan Urheiluhalli

Despite it being a practice session, full team scrimmages were being played throughout the whole measurement period, therefore the situation can be considered similar to a real match scenario. Viewers were not allowed into the stadium, and only the players and coaches were present.

All of the frequency bands are below 60 dBA, and the main peaks appear in the high frequency areas. This is because the only sound sources are coming from the court itself, particularly voices and sounds associated with basketball games (i.e., ball impact sounds and shoe squeaks). These values increase from the players' perspectives as they are closer to the source, but they are not expected to reach excessive levels nonetheless.

It is important to reiterate that the measurement period for each position was two minutes long, and some recordings were carried out while the action was paused for different reasons, such as a water break or a player shooting free throws.

The single number quantity for L_{Aeq} is 66.2 dBA.

4.2.2 Normal Scenario

The normal scenario is from a physical education class for elementary school children in the Tapiola school. There were six total measurement positions. The results are shown in Figure 23.

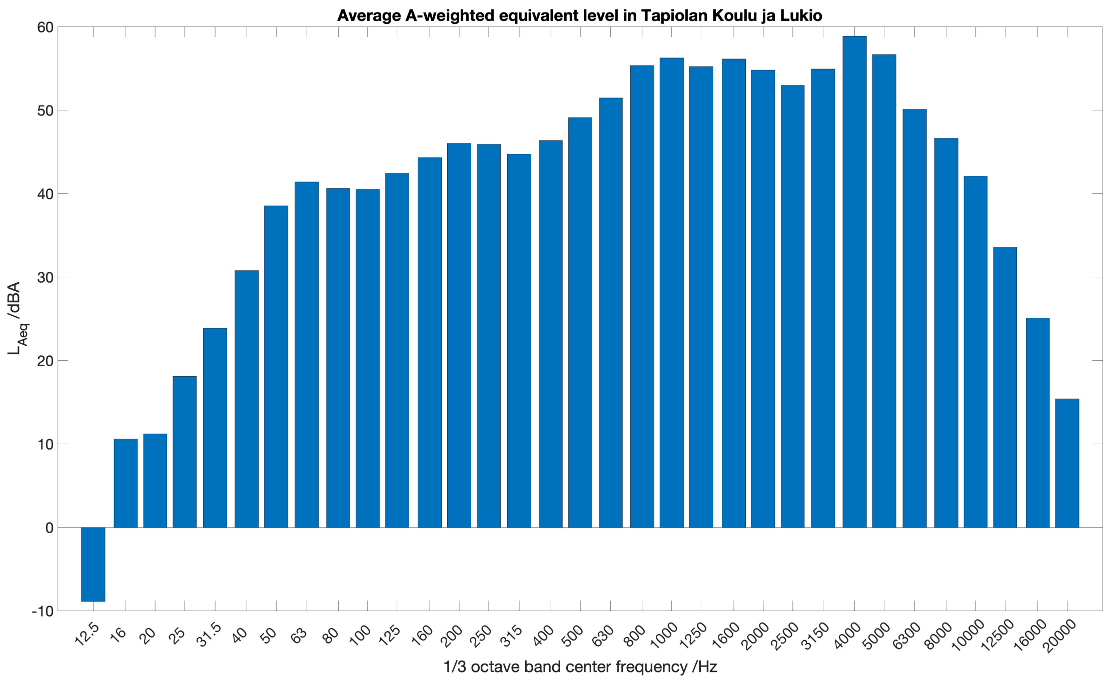

Figure 23: Average L_{Aeq} in Tapiola school

The gymnasium divider was lowered and the children were split into two groups on each side. Only one of the two simultaneous sessions was recorded.

The main sound sources were voice and impact sounds, as they were playing various ball games throughout the measurement period. Five of the measurement positions were on the gymnasium floor level, and the last one was placed on a raised stage (likely used for school plays or productions) on one side of the gym. The stage was not split in half due to the divider, therefore some sound from the other session was able to leak into the measured one.

All of the frequency bands are below 70 dBA, with the main peaks appearing between 1 and 2 kHz. The overall shape of the spectrum is similar to the previous scenario, with less high frequency components.

The single number quantity for L_{Aeq} is 74.8 dBA.

4.3 Computed Data

Results for both reverberation time and STI are presented in this section. As mentioned in the previous chapter, this data has been calculated from the measured impulse responses of each hall.

4.3.1 Reverberation Time

Figure 24 shows the reverberation time in one third octave bands for each sports hall.

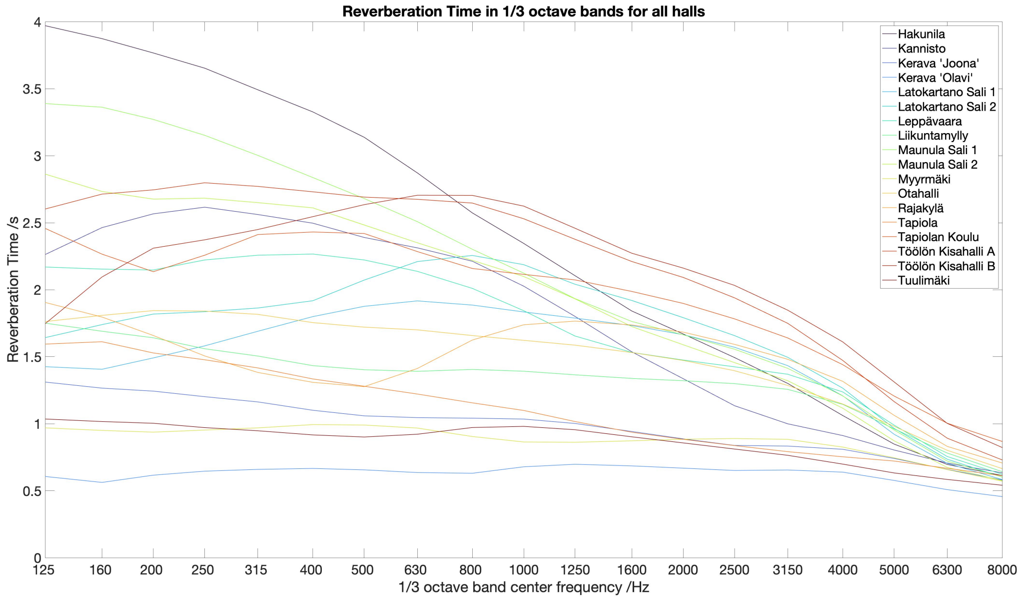

Figure 24: Common plot for reverberation time

The overall trend, as expected, is that reverberation time decreases as frequency increases. Some halls have steeper gradients, and some exhibit low variance in T_{60} values across the frequency range.

In order to analyze the results in more detail, they are grouped up based on the halls' structural characteristics, as well as the shape of their T_{60} curves. The curves are split as follows.

- Underground shelters;
- Mid-frequency peaks;
- Tapiola school;
- Everything else.

There were four halls located in three separate underground shelters: Hakunila, Maunula, and Tuulimäki. The curves for these halls are shown in Figure 25.

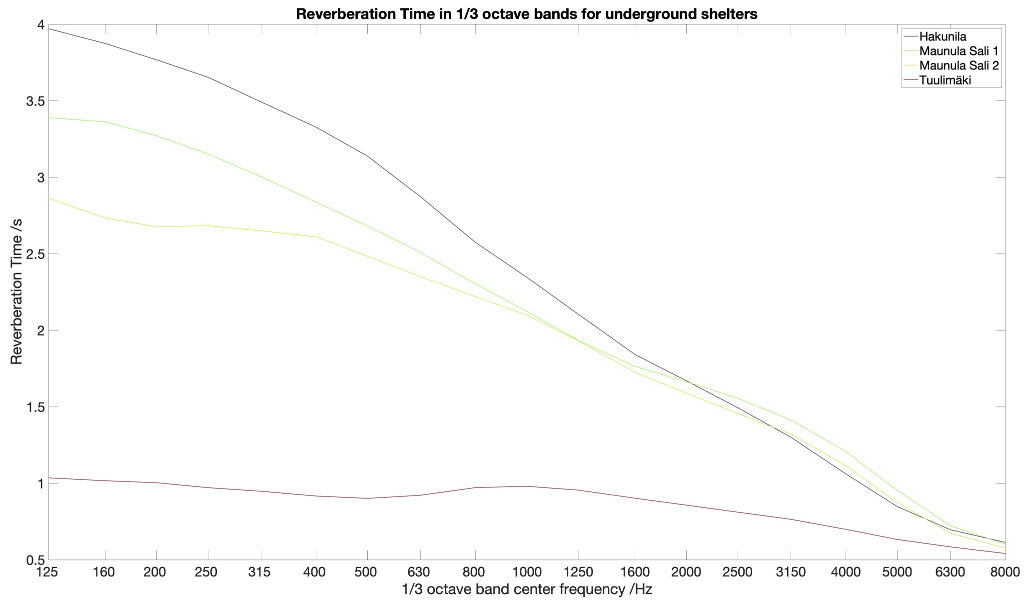

Figure 25: Reverberation time curves for underground shelters

The halls in Hakunila and Maunula show very similar results, with a maximum value at the 125 Hz octave band, and a steep gradient. The hall in Tuulimäki, on the other hand, exhibits consistent T_{60} values across the frequency range.

While all halls have a concave ceiling carved out of rock, the floors are different between the first three and Tuulimäki. The hall in Tuulimäki is used for gymnastics purposes, and the floor is therefore covered by padded, softer material. Additionally, there are mats, mattresses and foam pits, as well as various gymnastics apparatuses in the space. Acoustic reflections off the floor are therefore significantly diminished, resulting in low reverberation times.

The other halls are intended for team sport applications, such as basketball, floorball, or handball, and therefore have hard floor surfaces, leading to a higher proportion of incoming sound energy to be reflected off of them. The two halls in Maunula show almost the same values after 800 Hz, and the difference in the lower frequency range can be attributed to the fact that half of the floor in Sali 2 was covered with a judo tatami at the time of measurement.

There were four halls that displayed prominent peaks in the middle frequencies. These were in Latokartano, Rajakylä, and B-Halli in Töölö. Their curves are shown in Figure 26.

All of these halls are within above ground structures.

The maximum points in these curves are in the mid-frequency range due to the lightweight construction of the hall structures. If the walls and ceiling are sufficiently thin, it allows the lower frequencies to pass through them instead of being reflected back, in contrast to the underground shelters, where the boundary between air and wall is several meters of solid rock. Windows also have a significant effect on sound leaking out of the structure.

The Rajakylä facility exhibits a stranger shaped curve, likely due to its unique

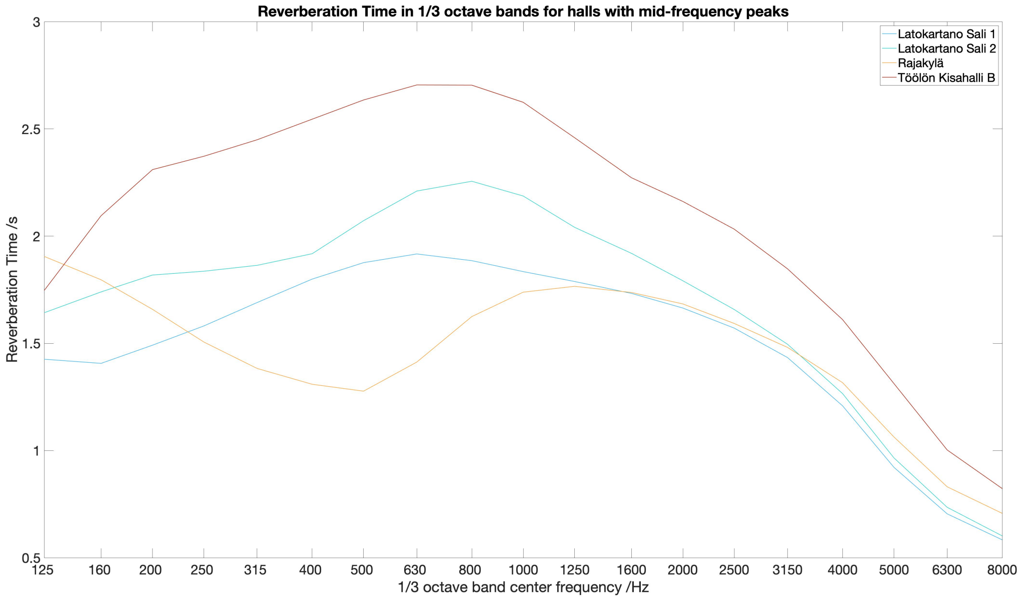

Figure 26: Reverberation time curves with mid-frequency peaks

structure. It is a tennis center with a floorball court at one end of the dome, which is where measurements were taken. These domes are typically made out of lightweight vinyl-coated polyester fabrics, supported by wooden beams. The floorball court was separated from the tennis courts by a large curtain, similar to a gymnasium divider, which covered most (but not all) of the space between the courts.

The Tapiola school was separated from the rest of the halls as its curve is heavily affected by an acoustic problem. During the measurements, a pronounced echo was present when the speaker was placed in the middle of the basketball court, which is also directly under the gymnasium divider. This echo was not distinctly audible in the other two speaker positions. Figure 27 shows the results for the first speaker position separated from the rest of them, to highlight this issue.

The two curves are similar in shape, with the first position curve having more pronounced peaks and dips. The difference in reverberation times is significant until around 800 Hz, after which point the results are almost identical.

The echo heard is referred to as flutter echo. This occurs when acoustic waves are trapped between two parallel surfaces, quickly reflecting back and forth, and creating an rapidly beating type of sound.

Lastly, the remaining curves are all shown in Figure 28.

The upper three curves, namely Kannisto, A-Halli in Töölö, and Leppävaara, show slight increases in reverberation time in the 200 to 400 Hz range, but not as significant as the mid-frequency peaks shown previously. The rest of the curves show a steady decline in reverberation time along the frequency range, or remain consistent throughout.

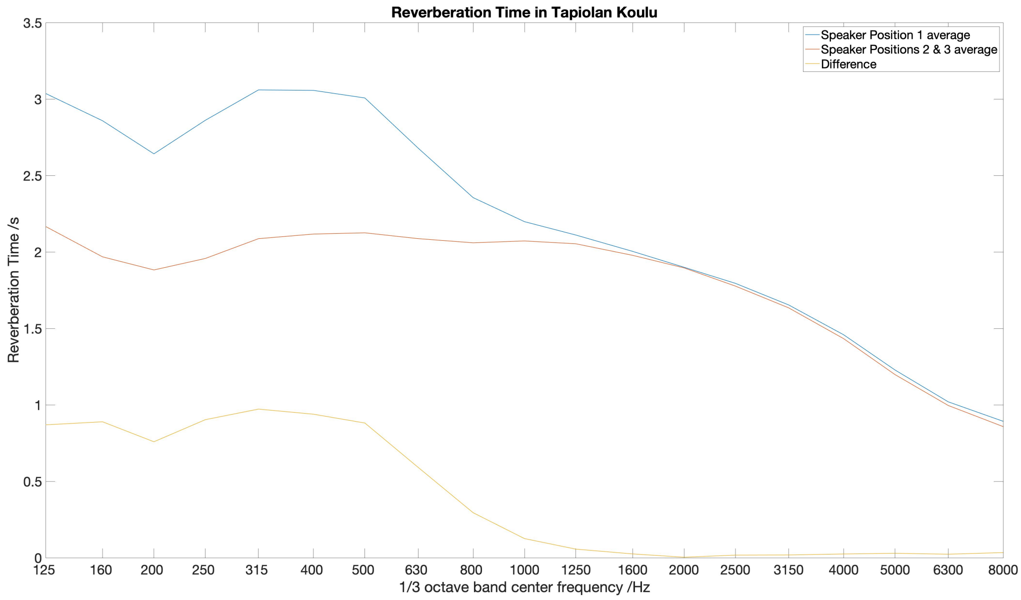

Figure 27: Reverberation time curves for Tapiolan koulu

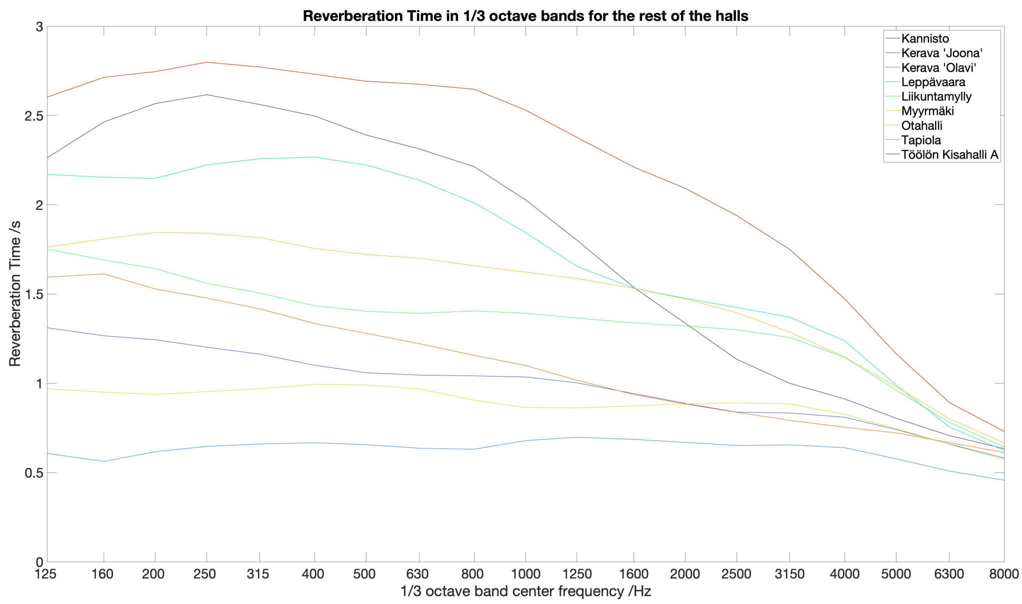

Figure 28: Reverberation time curves for the remaining halls

4.3.2 Speech Transmission Index

Figure 29 shows the average STI values, across measurement positions, for each sports hall.

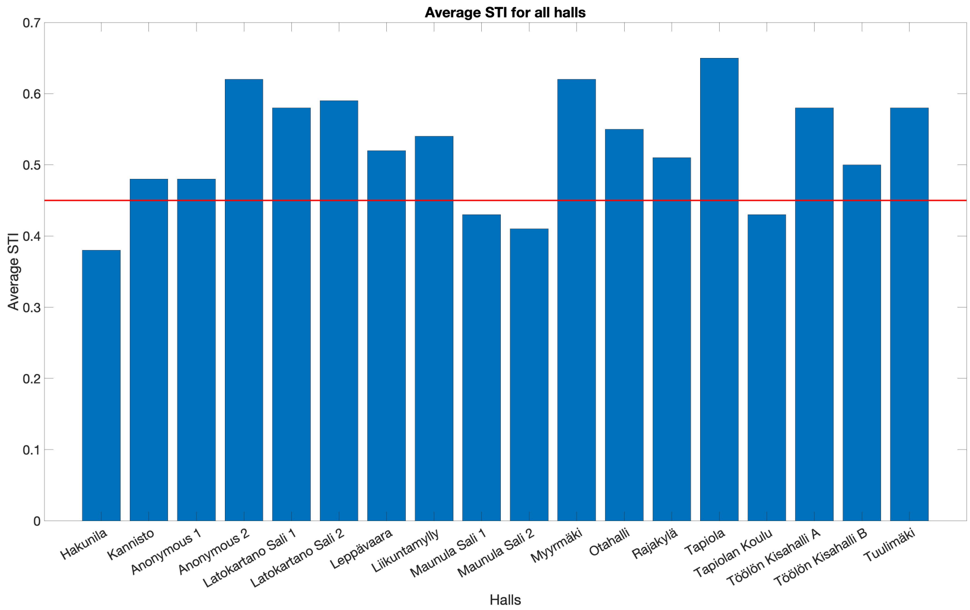

Figure 29: Average STI for all halls

As mentioned in Chapter 2.3.4, a value of 0.45 (indicated by the red line on the graph) is considered fair in most situations. There are four halls that fail to meet this value, namely in both the halls in Maunula, as well as the ones in Hakunila and in the Tapiola school.

STI is affected by multiple factors, including reverberation time and distance. The low values for Hakunila (0.38) and Maunula (0.43 for Sali 1, 0.41 for Sali 2) can be attributed to the very high reverberation times that were measured in those locations. The Tapiola school's STI value (0.43), on the other hand, can be partially attributed to the flutter echo problem that was noticed there. In Figure 24, the first speaker position's STI value is 0.39, whereas the other positions have a value of 0.45.

Only three halls exhibit "good" STI values (i.e., above 0.6), namely Tapiola, Myyrmäki, and 'Olavi' in Kerava. The halls in Latokartano, A-Halli in Töölö, and Tuulimäki are all under this threshold by only 0.01 or 0.02.

The STI values for each measurement position in each hall were also plotted against microphone distance from the source, and a trendline was generated for each set of data, to investigate the general pattern of how distance affected the results. This is shown for all halls in Figure 30.

The average gradient of the trendlines is -0.0124, which predicts an STI drop of around 0.12 every 10 meters away from the source.

Both the halls in Töölö have the highest predicted STI values at very close distances, but also exhibit the steepest gradients (around -0.03) leading to a predicted drop in STI of about 0.3 every 10 meters.

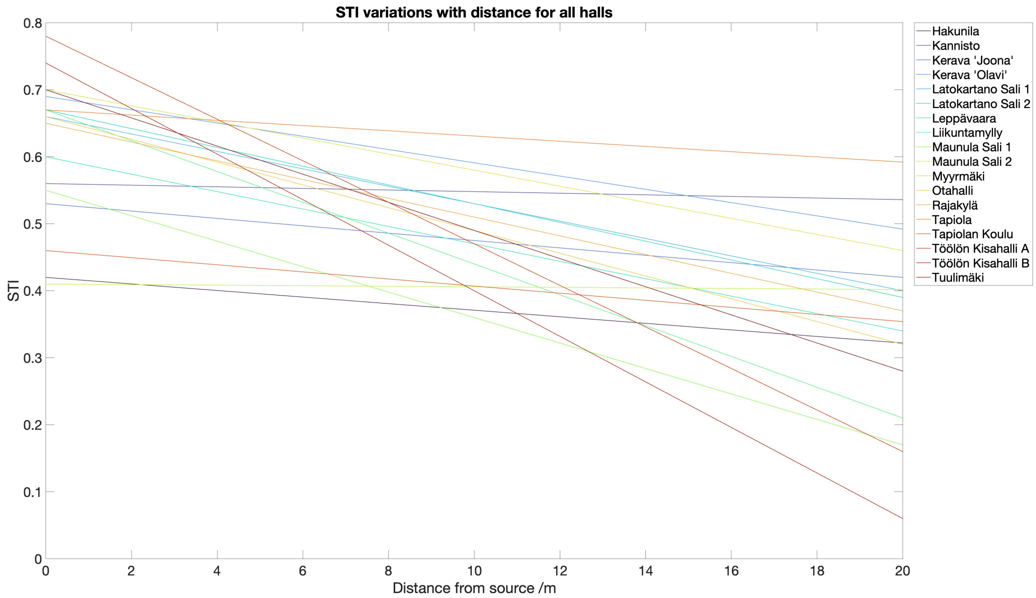

Figure 30: STI against distance for all halls

The most consistent hall is Sali 2 in Maunula, with a gradient of -0.00041. While this indicates that STI does not worsen significantly with distance, the starting value is below the satisfactory threshold nonetheless.

It is important to note that these trendlines do not accurately reflect the measured values, as their purpose is only to fit a linear pattern to the data. The main purpose of this plot is to predict the extent of the severity of the impact that distance has on STI.

5 Discussion of Results

This chapter goes into more detail on the meaning of the results, as well as the limitations of the current acoustic regulations. Ways to improve the acoustic environment in select locations are then suggested where applicable.

Due to the difficult circumstances caused by the restrictions in response to the Covid-19 pandemic, the noise level measurements were limited to only a few halls. These results were also largely not representative of what a normal situation would be like, therefore this aspect of the thesis would require further data collection once the pandemic situation is resolved. The average L_{Aeq} figure in the most realistic scenario (the Tapiola school) was 74.8 dBA over a two minute period. Typically a value of 85 dBA over eight hours is used as a limit for occupational noise, indicating that the measured data is well within reasonable values for exposure.

The results were split into different categories due to the variety of data that was collected. The measurement methods were kept as similar as possible between locations in order to keep this variety to a minimum, as it was expected that the differences in structure geometry would have a significant impact on the results. It is for this reason that the current regulations are deemed to not be comprehensive enough for the specific case of sports halls. Compared to rooms such as open plan offices, which are more standardized, sports halls can be built in a wide range of building styles, using a wide range of materials. This contributes to varying reverberation time values that can be deemed acceptable by occupants of the space.

5.1 Limitations of Regulations

As mentioned at the beginning of this thesis, reverberation time alone is not necessarily a reliable absolute indicator of the acoustic environment quality in a space. For example, despite failing to meet the limit values for reverberation time, the A-Halli in Töölö and both the halls in Latokartano have some of the highest STI values out of the measured locations, just under the threshold for "good". This would indicate that communication between occupants is predicted to not have significant issues.

The survey that was planned to take place during the measurement period, and data from which was going to be part of this thesis, would have provided a useful indicator of how occupants would have rated the acoustic environment. Ultimately this is what would have proven whether the regulation limits were applicable in certain situations or not.

The RIL regulation [8] had two sets of limit values, the difference between them being the ceiling height within the space: over or under 5 m. While this can be a sensible aspect to look at, it can only be effectively applied to certain geometries that feature a constant ceiling height (e.g., box shaped halls). In underground shelters, the ceiling is concave, and therefore has a different height at each point along the arch. In this thesis, the apex of the arch was chosen to determine whether the ceiling was over or under 5 m. The RIL regulation therefore cannot be accurately applied to this type of situation.

The Environment Ministry regulation [17] specifically mentions sports halls as a building type. However it only applies to those under 1500 m^3 in volume, which has been shown to be extremely limited.

5.2 Suggested Improvements

There were two standout issues across all the measured halls, namely the extremely high reverberation times in the underground shelters, and the presence of flutter echo in the Tapiola school. This section suggests possible steps than can be taken to improve the acoustic environment by alleviating these problems.

The suggested improvements are mainly aimed towards reducing reverberation time, but will contribute to the improvement of Speech Transmission Index (STI) values as well.

5.2.1 High Reverberation Times

The data in Tuulimäki does not follow the same pattern as the other shelters, however this is due to the presence of gymnastics equipment throughout the space. It is sensible to assume that other halls within the complex, such as the table tennis room, would exhibit similar reverberation time curves to the measured halls in Hakunila and Maunula.

The high reverberation times in underground shelters can be attributed to the hard surfaces that enclose the spaces. The walls and ceiling can be grouped together as they form the concave arch structure made out of solid rock thick enough to avoid any frequency from going through it. Acoustic waves behave similarly to light waves, and therefore when they interact with a concave boundary, the energy will be focused towards a specific area, as shown on the left side of Figure 31.

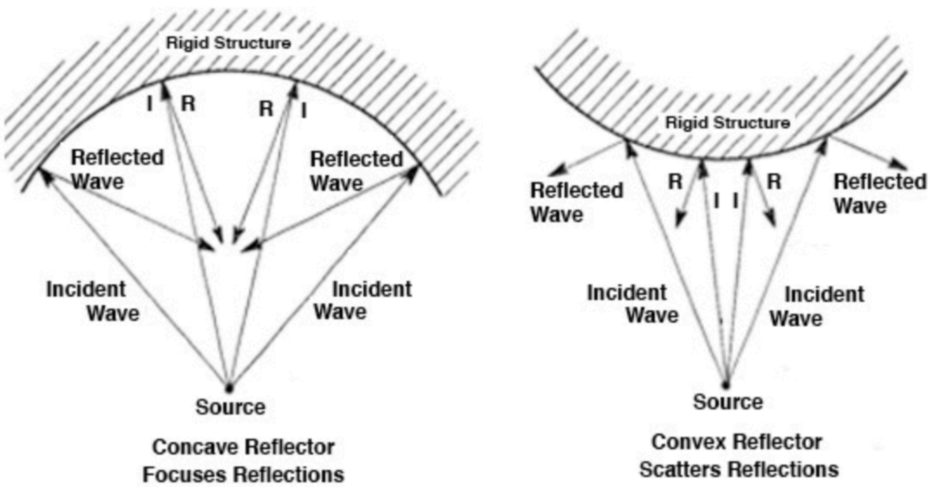

Figure 31: Acoustic wave behavior against concave and convex reflectors. Reprinted from [46]

Higher frequencies tend to focus more energy into smaller areas, whereas lower frequencies spread out more after reflection [47]. This provides another possible reason why reverberation time was higher in the lower end of the frequency spectrum (in addition to the fact that lower frequencies decay at a slower rate): if the focusing area is larger, it will be perceived by a bigger proportion of the room compared to the higher frequencies. Averaging of multiple measurements would therefore have a lesser impact on reducing the impact of anomalies in some measurements.

Concave surfaces are generally undesirable in contexts such as music halls due to the acoustic focusing that they cause. Typically the aim is to ensure a consistent listening experience for the audience across all seating positions. Diffusion is commonly used as a technique to reach this aim. As shown in the right part of Figure 28, convex reflectors scatter the incoming sound over all directions (i.e., the opposite of concave reflectors). A perfectly diffuse environment is one where the reverberation time is equal in any point in the space.

While diffusion is an effective technique for providing a good acoustic environment in the context of theaters and music performance halls, the acoustic aims for sports halls are different. Especially in the cases of the problematic underground shelters highlighted in this thesis, the main issue is the persistence of acoustic signals within the space. Diffusive reflectors would not be effective in reducing reverberation time as acoustic energy is just redirected rather than attenuated.

It has been stated that the main factor contributing to the high reverberation times in the shelters is the material of the enclosing surfaces. Rebuilding these facilities is not an option, therefore steps must be taken to change both the geometry and the total absorption of the hall. Looking back at Equation 8 (p. 21), the latter would mean increasing the value of a. Increasing the total absorption of the hall would contribute to taking acoustic energy out of the system, therefore reducing the persistence of sound.

Acoustic panels have been widely used in many different situations to increase the total sound absorption of a room. This is most notable for example in recording studios, where being able to exclusively hear the direct sound coming from the monitor speakers is essential to music production. As the issue of reverberation time in the underground shelters is most prominent in the low frequency range, an example of a suitable acoustic panel is shown in Figure 32.

Acoustical Performance - Absorption Coefficients							
ASTM C 423 test with 48”x48” test specimens. Results may vary dependent on size of panels.							
Frequency (Hz)		100	125	250	500	1K	2K
ATP 2.0L	2” Panel	0.58	0.61	0.35	0.35	0.25	0.18
ATP 2.0LBB	2" Panel	0.47	0.73	0.76	0.95	0.96	0.98
ATP 4.0L	4” Panel	0.78	0.54	0.41	0.37	0.25	0.18

Figure 32: Low frequency acoustic panel absorption data. Reprinted from [48]

These panels are made out of fiberglass material, with a membrane resonator that can be selectively tuned. The ATP 2.0LBB panel would be the most suitable for this specific case as acoustic regulations start at 125 Hz, therefore very high absorption under this frequency is not the highest priority. Reverberation times in all of the three problematic shelters exceed regulations from 125 to around 1600 Hz, and the absorptive characteristics from such a panel would have a significant impact towards lowering the values close to the limits.

Three out of the four sports halls that exhibited mid-frequency peaks in their reverberation time curves did not meet the regulation limits, namely the B-Halli in Töölö and both the Latokartano halls. The frequency ranges that exceeded limit values were between 250 and 2000 Hz for Töölö, 500 Hz for Latokartano Sali 1, and between 500 and 1000 Hz for Latokartano Sali 2. An example of a suitable acoustic panel for these cases is shown in Figure 33.

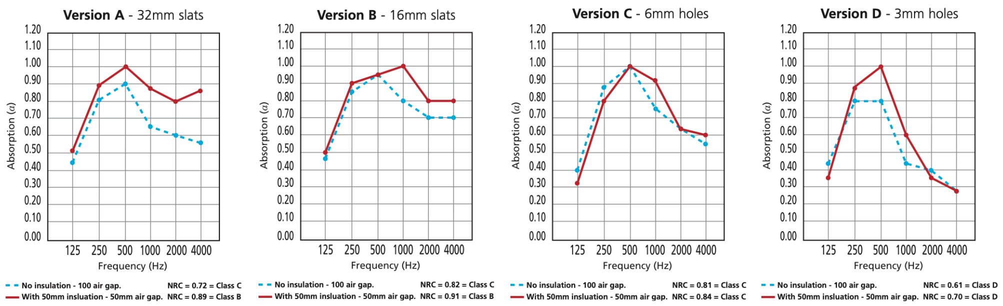

Figure 33: Mid-frequency acoustic panel absorption data. Reprinted from [49]

These panels have multiple layers, the main ones being an acoustic fleece covered by a wooden surface, which either has slats or holes drilled onto it. The slats are either 32 (Version A) or 16 (Version B) mm apart, and the holes are all 16 mm apart, regardless of their diameter.

The absorption data suggests that Version B would be most suited to Töölö. Version C would be most suited to both of the halls in Latokartano. While installation would be simple for the latter halls as these panels can be fitted to the walls, the B-Halli in Töölö has bleachers and therefore installation can predictably be more complicated in terms of panel location.

Lastly, some low frequency attenuation would be beneficial to the A-Halli in Töölö, as well as the halls in Kannisto and Leppävaara, in order to meet the regulations.

5.2.2 Flutter Echo

As mentioned in Chapter 4.3.1, the gymnasium in the Tapiola school had a distinct echo problem when the speaker was placed in its first position, under the divider. Known as flutter echo, this happens when sound is trapped between two close parallel surfaces, and causes a rapidly beating sound to occur.

As shown in Figure 24, the echo had a significant effect on the reverberation time at the lower part of the frequency range. Both diffusion and absorption could be applied in order to attenuate this issue. By spreading out incoming acoustic energy across all directions, diffusive panels would reduce the proportion of energy that is trapped where the echo is being produced, therefore reducing its level. However, due to the fact that the STI value is low (0.45) even when removing the first speaker position, diffusion would likely not improve the overall STI for the hall significantly. Absorption would be the most effective solution in this situation, located specifically where the flutter echo is present. Removing acoustic energy through absorption would again lead to less energy being trapped.

Since the gymnasium divider itself appears to be the likely cause of the issue, considerations could be made towards replacing this element of the structure. However, this is outside the scope of this thesis.

6 Conclusions

This thesis has investigated the acoustic environment in 18 sports halls around the Helsinki metro area in terms of three commonly used acoustic parameters, namely reverberation time, Speech Transmission Index (STI), and A-weighted noise level. This was done as the acoustic part of the LIIKU project, which aims to investigate the overall indoor environment quality in sports halls.

In researching regulation regarding acoustic parameters for sports halls specifically it was found that this is insufficiently developed, not only in Finland, but in other countries around the world as well. Acoustic regulation is often developed around ordinary rooms in households, open-plan offices, or performance spaces (e.g., theaters). Regulations are also not applicable retroactively, meaning that existing structures with poor acoustic environments are not required to improve them, even following renovation work. An additional aim for this thesis was subsequently discovered: the data gathered and results produced could provide grounds for the development of comprehensive acoustic regulation for sports halls.

The measurements were taken in adherence with standardized practices and equipment. The measurement process was kept as similar as possible in each location in order to minimize the number of individual factors that could affect results. Established methods like the Farina deconvolution method were used to process the data in order to produce the best quality results possible.

The quality of the results did not always reach the initially expected levels due to Covid-19 restrictions. The noise level measurements were limited and not representative of a normal situation, and the subjective results had to be excluded from the scope due to delays in survey administration. The impulse response measurements required empty spaces, and therefore were unaffected by restrictions.

Around half of the measured sports halls were found to be in compliance with the current acoustic regulations. However, there were certain halls that, despite failing to meet reverberation time limit values, exhibited better STI values than compliant halls. The latter point likely indicates that even the some non-compliant halls could have good acoustics for occupants, and this could potentially have been confirmed by the survey data. This confirms the notion that reverberation time alone is insufficient to determine the quality of an acoustic environment, and therefore points out the fundamental issue with current acoustic regulation.

The results also identified acoustic issues within some facilities, under the form of extremely high reverberation times or the presence of flutter echo. These problems, coupled with the unsatisfactory STI values that were also found, confirm the presence of a poor acoustic environment within the specific facilities, and efforts should be made to alleviate these problems.

Although outside the scope of this thesis, potential solutions for the discovered acoustic issues were suggested. Both diffusion and absorption techniques were considered, and it was concluded that removing acoustic energy from the hall would be the best solution to reduce reverberation time, which also contributes to the improvement of STI. This is done by increasing the overall absorption of the surfaces within a space, for example through the installation of acoustic panels on walls or ceilings, targeted mainly towards specific problematic frequency ranges (the low end for underground shelters, and the mid-frequency range for structures featuring lightweight construction).

6.1 Directions for Future Work

Overall, this thesis can be considered as the start of a process towards the development of comprehensive acoustic regulation for sports halls (i.e., the identification of the problem). The first step would be to also include STI limit values in regulation alongside reverberation time; it has been shown that good STI values can be achieved even when reverberation time exceeds limits. STI is affected by more factors than just reverberation time, and it is a closer indicator of occupant experience. Its inclusion would therefore be useful for the determination of other acoustic issues if reverberation time values were considered acceptable within a space, but STI values still turned out to be low.

The results show that the current regulations cannot define a good or poor acoustic environment in its entirety, and therefore must be amended. Another issue is that current regulations are not broad enough in scope to account for the variety of shapes and sizes that sports facilities can take.

The LIIKU project survey that was initially planned to be part of this thesis, and which will be carried out later this year, will provide useful subjective results from the occupants of each sports hall. This data can be used to evaluate if the measured results correspond to the actual experience that occupants perceive while in the facilities, and would therefore provide a more informed basis for the decisions behind development of new limit values for acoustic parameters. Future work would likely seek to develop a set of categories for sports facilities, based on both their shape and intended purpose. Example categories could be underground facilities, single hall facilities, and multi hall facilities. The latter would refer to places such as Liikuntamylly, where the basketball court that was measured was part of a larger complex including an athletics track, a weight gym area, and other team sport courts, with minimal physical separation between each area (i.e., walls did not completely isolate each space from the others).

Another important aspect of the redevelopment of acoustic regulation is the dimensions considered when differentiating between sets of limit values. The RIL regulation uses ceiling height, which is insufficient due to the fact that it is a one dimensional measure. This can be problematic in cases such as the underground shelters, where ceiling height is not the same everywhere in a hall.

The Sabine equation calculates reverberation time in terms of volume and total absorption. Volume should therefore be the reference quantity for defining sets of limit values. The Environment Ministry regulation uses volume to define building categories, but only includes sports halls under 1500 m^3. As the vast majority of sports halls exceed this value, the regulation should be expanded to include more volume brackets.

The essential aspect to any regulation, whether it be existing or new, is to make sure that it applies retroactively to existing structures, requiring adjustments to be made. In an ideal scenario, these adjustments would be immediate and similar to those suggested in the previous chapter. However, the cost of such procedures can be prohibitive in many cases, and there are simpler solutions that can still help attenuate acoustic issues, even if not as effectively as specialized acoustic panels. An example would be placing fabric curtains in front of walls: the soft material would provide more absorption than a hard wall. Halls such as Tapiola and Myyrmäki already have curtains covering parts of the walls.

Preemptive measures are important for all occupants of sports halls, as acoustic issues are generally not immediately obvious, and even relatively minor annoyances or discomfort can lead to health issues in the long term.

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